Southeastern Geology: Volume 43, No. 1
August 2004

Editor in Chief: S. Duncan Heron, Jr.

Abstract

Academic journal published quarterly by the Department of Geology, Duke University.

SOUTHEASTERN GEOLOGY

Vol. 43, No. 1

August 2004

SOUTHEASTERN GEOLOGY

PUBLISHED

at

DUKE UNIVERSITY

Editor in Chief:

Duncan Heron

This journal publishes the results of original research on all phases of geology, geophysics, geochemistry and environmental geology as related to the Southeast. Send manuscripts to **DUNCAN HERON, DUKE UNIVERSITY, DIVISION OF EARTH & OCEAN SCIENCES, BOX 90233, DURHAM, NORTH CAROLINA 27708-0233**. Phone: 919-684-5321, Fax: 919-684-5833, Email: duncan.heron@duke.edu Please observe the following:

1) Type the manuscript with double space lines and submit in duplicate, or submit as an Acrobat file attached to an email.
2) Cite references and prepare bibliographic lists in accordance with the method found within the pages of this journal.
3) Submit line drawings and complex tables reduced to final publication size (no bigger than 8 x 5 3/8 inches).
4) Make certain that all photographs are sharp, clear, and of good contrast.
5) Stratigraphic terminology should abide by the North American Stratigraphic Code (American Association Petroleum Geologists Bulletin, v. 67, p. 841-875).
6) Email Acrobat (pdf) submissions are encouraged.

Subscriptions to *Southeastern Geology* for volume 43 are: individuals - $23.00 (paid by personal check); corporations and libraries - $33.00; foreign $40. Inquires should be sent to: **SOUTHEASTERN GEOLOGY, DUKE UNIVERSITY, DIVISION OF EARTH & OCEAN SCIENCES, BOX 90233, DURHAM, NORTH CAROLINA 27708-0233**. Make checks payable to: *Southeastern Geology.*

Information about SOUTHEASTERN GEOLOGY is on the World Wide Web including a searchable author-title index 1958-2001 (Acrobat format). The URL for the Web site is: http://www.southeasterngeology.org

SOUTHEASTERN GEOLOGY is a peer review journal.

ISSN 0038-3678

SOUTHEASTERN GEOLOGY

Table of Contents

Volume 43, No. 1 August 2004

SOUTHEASTERN GEOLOGY
V. 43, No. 1, August 2004, p. 1-20

LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS OF THE PLIOCENE CITRONELLE FORMATION, GULF OF MEXICO COASTAL PLAIN

ERVIN G. OTVOS

Department of Coastal Sciences
University of Southern Mississippi
Ocean Springs, MS 39566-7000
ervin.otvos@usm.edu

ABSTRACT

Citronelle, the most extensive surface unit in the Gulf of Mexico coastal plain, has been interpreted as the product of braided streams that carried coarse bedload. Granulometric analysis of more than 900 samples suggests the role that fine-textured deposits have also played in the aggradation of Citronelle flood plains. Mud, muddy sand, and intraformational mudclasts are prevalent, and 0.5-to-5.0 m thick lacustrine flood plain clay and mud deposits that locally display cylinder and pipe-mold structures of vegetational origins are also common. Secondary banding in sand, due to interstitial iron oxide/hydroxide pigment translocation, is widespread. In addition to braided models, meandering, transitional meandering-braided, anastomosed, and/or gravel-sand meandering fluvial styles should not be excluded from consideration of the probable styles of Citronelle fluvial architecture. Pollen data and widespread estuarine highstand facies reconfirm the Pliocene age. Deflation and other widespread surface processes, impacted by superimposed pedogenic influences, account for the post-Citronelle "cover sand interval." Substantial uplift of the gently Gulfward-inclined regional Citronelle surface, kaolinite-filled orthogonal fracture networks, fracture- and fault-defined terrace sectors, stream channel networks, and localized steep shoreward tilt of local sediment intervals reflect the contribution of tectonism to the surface topography.

INTRODUCTION

The Citronelle Formation (Matson, 1916) represents the most widespread coastal unit between the Texas and south Georgia. It overlies lower Pliocene siliciclastic sediments; in the east, carbonates (Isphording and Flowers, 1983; Otvos, 1997, 1998). In contrast with the fine-grained Mississippi River suite, coarse sandy-gravelly deposits, considered deposits of braided bedload rivers, are common. A preliminary evaluation of granulometric characteristics was based on many exposures in a four-state area. Textural and structural characteristics display a remarkable overall similarity in range and frequency across the Citronelle distribution area (Appendix). Because fine-grained lithofacies appear to be more widespread than previously assumed, non-braided stream models should also be considered when determining the formation's fluvial architecture.

Influenced by uneven antecedent topography, Citronelle thickness values range between 5 and 75 m (Self, 1986; Smith and Meylan, 1983; Otvos, 1997). Even far downdip, thin Citronelle intervals overlie a pronounced Miocene-Pliocene erosional unconformity in the Mobile Bay area (Isphording, 1976; Isphording and Flowers, 1983). Extending from below sea-level along Mobile, Perdido, and Escambia Bay shores, the gently inclined Citronelle surface rises landward to +180 m in central Mississippi (Boswell, 1979) and adjacent states. Previously widely considered as Pleistocene, pollen content, correlation with coeval fossiliferous units to the east (Huddlestun, 1988), its high elevation and inland extent, and the thick enclosed estuarine sediment interval help to reconfirm a Pliocene age (Otvos, 1997).

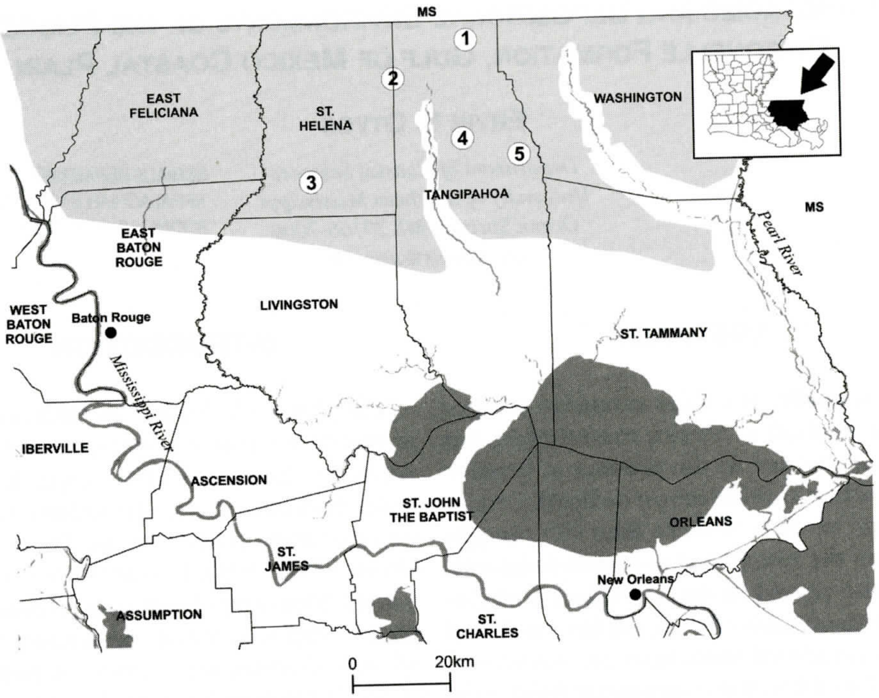


Figure 1a. Locations of Citronelle sampling sites, southeastern Louisiana. Citronelle distribution areas shaded in Figures 1a-to-1d.

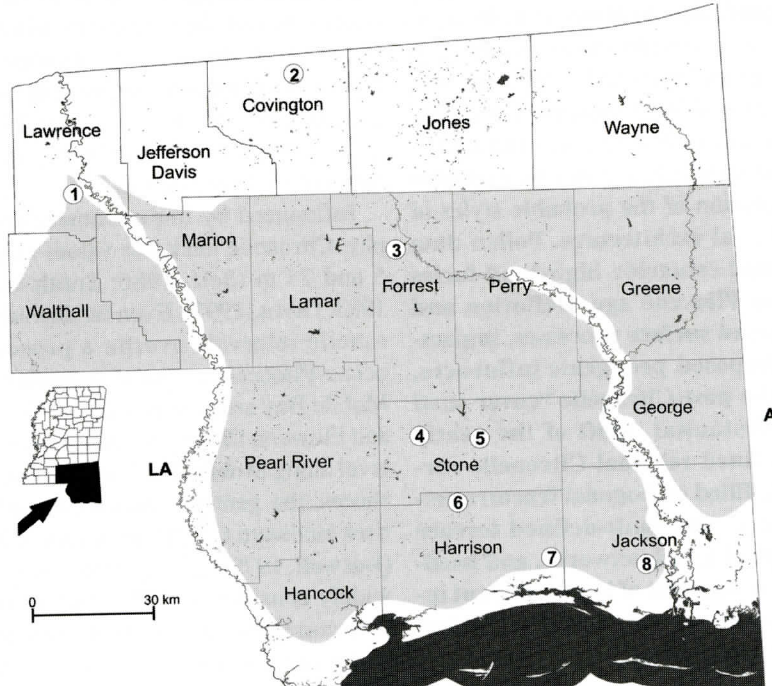


Figure 1b Location of Citronelle sites, Mississippi.

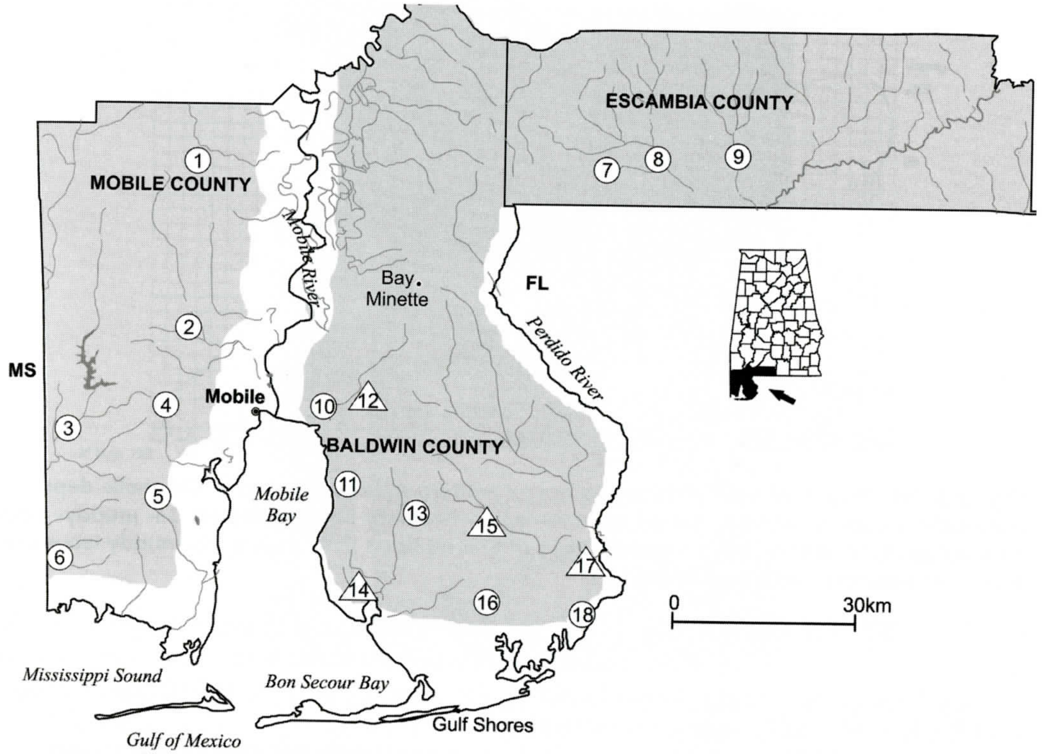


Figure 1c Location of Citronelle sites, south Alabama. Location numbers with estuarine sites in Figures 1c and 1d in triangles.

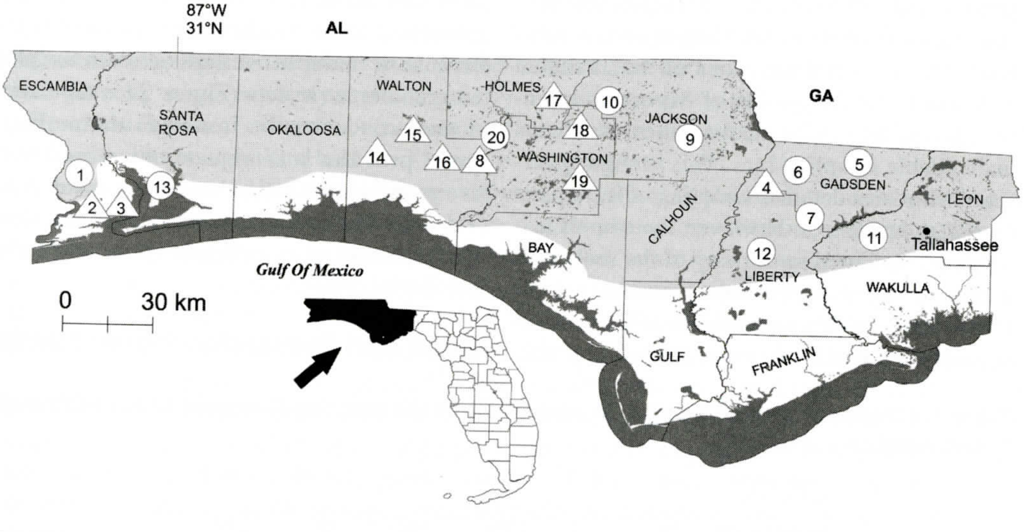


Figure 1d. Location of Citronelle sites, NW Florida.

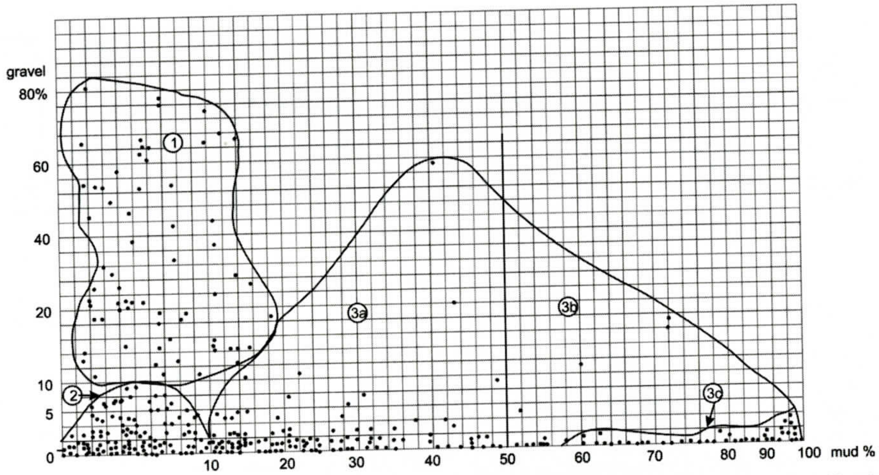


Figure 2. Distribution of mud and granule-gravel content in sampled alluvial Citronelle deposits. Data point fields: 1- gravelly-sandy channel facies 2- sandy channel facies; 3a- muddy- sand channel bank-flood plain environments; 3b- sandy-mud flood plain facies; 3c- muddy lacustrine and other fine-textured fluvial facies.

STUDY METHODS

Granulometric data were obtained by standard Ro-Tap sieve and pipette analyses (Folk, 1961). A total of 939 samples was processed from 135 sites. The Appendix and four index maps (Figs. 1a-d) indicate site locations by USGS quadrangles. Because they target thick gravel-sand rich intervals near population centers, the more detailed sampling at certain locations, the uneven dimensions of the available exposures, and the quality of exposures representing variable sediment diversities introduced unavoidable sampling bias. This is slightly offset by similarly detailed sampling of infrequent mud-clay sequences. However, the overall textural and structural uniformity of the sediments across the region suggests the presented sample record is reasonably representative. Clay mineral composition in 17 sites was analyzed by standard smear slide preparation technique and X-ray diffractometer with theta compensating slits, counting for 1 sec. at 0.02 degree steps.

LITHOFACIES CATEGORIES

Lithofacies categories were grouped according to dominant grain size. Sedimentary structures and other relevant features were also considered in the evaluation of sediment types. Because of multiple overlaps between the plotted granulometric data (Figure 2), a tabulation of mud concentration in non-estuarine lithosomes provided a semiquantitative but extensive general information base on sediment types (Table 1). The data may contribute to establishing the identities of different Citronelle facies and fluvial styles.

Sand and Gravel-dominated Fluvial

Table 1. Frequency of mud fraction in alluvial Citronelle samples (Samples of post-Citronelle "cover sand unit" excluded)

mud content range, in %	0-5	5-10	10-25	25-50	50-75	75-100
number of samples per mud content	195	126	174	128	69	155
percentage of samples	23.1	14.9	20.5	15.1	8.1	18.3

Figure 3. Planar tabular cross-sets in sandy channel setting. Downward percolating pigmented silt and sand grains and precipitated iron oxide outline irregular lamina interfaces and bounding surfaces. Ruler length: 48 cm Upward-filtrated pigmentation front (arrow; lower right) transects planar foreset unit, second from bottom. Site B-57N (Location 14; Figure 1c).

Deposits

Sand-dominated units. A broad continuum of sedimentary textures exists from virtually mud-free gravelly sands to sandy muds, to nearly pure muds (Figure 2). Vertical alternation of sand beds with muddy sand and mud layers is common even in or adjacent to predominantly coarse, thick gravelly sand and sand sequences. Medium and fine sands that include only a trace of mud or none are of white to light gray color and moderately well- to- very well sorted. Pigmentation by hematite and/or limonite, attached to clay and silt particles that coat sand grains produced reddish, pink, and orange-red colors. Only 5% hematite content in the kaolinite-gibbsite film on quartz grains results in deep red color (Otvos, 1997). Pale-yellow and reddish-orange hues appear when mud content reaches 0.9-2.0%. Increasing clay and silt concentrations result in darker yellowish-brown, reddish-brown, and reddish-orange colors. Light brown, pale yellowish-brown, and pale and grayish orange colors are also common. Incorporated dark orange-red intraformational sandstone clasts and dark reddish-brown hardpan fragments prove that pigmentation and limited cementation preceded completion of Citronelle deposition.

Common ripple cross-lamination and small-scale planar cross-bedding reflect low flow velocities in shallow channels (Figure 3). Coset thickness values generally range between 2 and 15 cm (Site B-23; Location 14; Figure 1c and Site W-1, Location 14 in Figure 1d). Higher current velocities in deeper channels formed less frequent, 0.4-1.0 m thick tabular foresets that consist of granular-sandy cosets inclined at angles of 15° to 40°. Alternation of 20 and 90 cm thick dark yellowish-brown sandy mud, sandy clay, and clayey fine sand beds with light brown pebbly-granular sand units of higher energy conditions and similar dimensions is common. The darker layers reflect slacker episodes

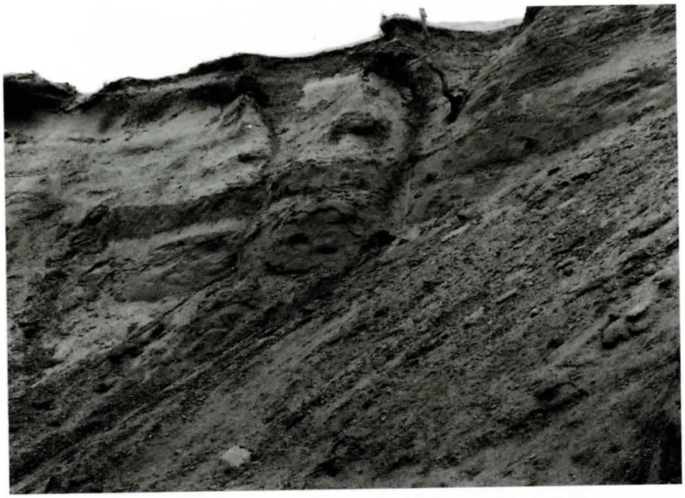


Figure 4a. Alternating, 20-100 cm thick dark red muddy sand and light yellow pebbly sand layers adjacent to thick sandy-gravelly fluvial sequence. (Site STO-2, Location 4 in Figure 1b).

Figure 4b. Thin alternating layers of muddy sand (darker) and granular sand (lighter). Site WASH-4 (Location 20 in Figure 1d). Highly unusual steep southward (left) dip may be of tectonic origin.

when muddy suspension load settled, even infiltrating underlying gravelly sand deposits (Figures 4a, b).

Interstitial translocation of clay-sized particles by circulating ground waters was a widespread secondary process in permeable sands. The accumulation of fine mud and pigment particles under pedogenic and phreatic conditions formed irregular- wavy illuvial "beta lamellae," also called "dissipation structures." They develop by the addition of interstitially transported clay minerals, colloidal matter, and/or by precipitation of hydrous iron oxides (Torrent et al., 1980; Shlemon, written comms., 1995).

In addition to beta lamellae, alternating thin red, orange-red and white bands are displayed in numerous outcrops. These formed by *downward* infiltration of pigment-bearing mud and/ or by iron oxide/hydroxide precipitation. Differential eluviation and dissolution of pigmented matter accompanied and followed the process. Controlled by permeability pathways, redox, pH, and other parameters, invading solution fronts were instrumental in shaping sec-

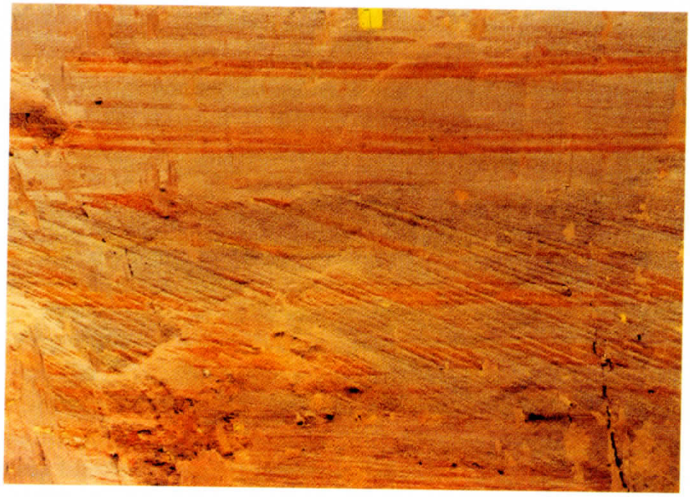


Figure 5. Horizontal red illuvial inflitration lamellae intersect inclined primary depositional lamination in planar dune foresets, similarly outlined by iron pigmentation. (Site STO-2, Location 4, Figure 1b). Ruler, in all figures in inch scale, visible length, top: 2.5 cm.

ondary banding. the result of iron oxide and hydroxide precipitation and dissolution episodes. Horizontal lamellae (Figure 5) or semicircular wavy bands of alternating red, yellow, and orange lamellae formed with intervening bleached, pigment-free intervals. In most locations, the pigmentation bands transect, or at least intrude on, primary layering.

Figure 6. Residual interlaminated red-and-white sand (bottom), separated from similar upper unit by zone of subsequent bleaching. Primary lamination runs continuously between bleached white sandy lithosome and the still pigmented round area. Trowel length: 26 cm. (Site M49 at Location 3; Figure 1c).

Pigmented matter concentrated along bedding plane surfaces and erosional interfaces between individual tabular cosets and between ripple laminae. Lenticular pigmented matter also outlines burrow walls and escape structures. Solution and suspendate fronts, driven by *rising* intrastratal water resulted in upward-arching convex bands (Figures 3, 5-6).

Gravelly units. A granule-and-gravel content that ranges from trace amounts to 50 percent prevails in the sands. Cross-bedded sandy gravel layers and gravel stringers, 0.2 to 4.0 m thick, at numerous sites are interlayered with coarse and medium sands. Gravel clasts, generally 1 to 4 cm long, locally reach 6 to10 cm. Most pebbles consist of chert, frequently friable tripoli chert, and quartz. Chert pebbles display silicified Paleozoic fossils that originated in south Appalachian carbonate rocks (Smith and Meylan, 1983). Matrix-supported textures are predominant in the sandy-gravelly deposits. Occasional 0.5-1.2 m thick yellowish-brown limonite-cemented sandstone, conglomerate, and hardpan ledges represent the only lithified near-surface deposits in the lower coastal plain.

Channel forms of variable dimensions are exposed infrequently (Figures 7a,b). Channel aggradation involved gravel and sand bars and formation of the "two- and three-dimensional" (2D and 3D) fluvial dunes of Miall (1996, p.109-112), characterized by planar and trough cross-bedding, respectively. Cross-laminated planar cosets and ripple cross lamination are also typical of channel sand lithosomes that alternate with coarser gravelly sands (Figure 3).

Fine-grained Fluvial Lithofacies; Cylinder and Pipe Structures as Flood Plain Indicators

In contrast with the mud-dominated Mississippi River flood plain, the Citronelle is coarser-textured but, contrary to assumptions, does frequently incorporate substantial volumes of muddy deposits. One-quarter of the analyzed samples derived from alluvial beds contains less than five percent mud. Another one-quarter included more than 50 percent mud and nearly half of the samples represent 10 to 100 percent mud content (Table 1).

Sand, muddy-sand, and sandy mud beds are often intercalated. This occurs even in the extensive, maximum 10-22 m thick sand and gravel lithosomes in the Hattiesburg, Red Bluff, Wiggins-Pearlington areas of Mississippi (Locations 1, 3-5; Figure 1b), and in Pit M-13,

Alabama (Location 5; Figure 1c). While 1.0-5.0 m thick clay and mud intervals are rare (Figures 8, 9), many Citronelle exposures observed display single or multiple clay-mud layers, often only 2-30 cm thick. The 1.2 m silty clay interval that filled a narrow, abandoned river channel at Site B-53 (Location 16 in Figure 1c) represents one of several modes by which mud had accumulated in the Citronelle flood plains. Red, purple, orange, yellow, or gray laminated lacustrine beds occasionally are of soft, plastic consistency. Poorly-rounded gray, white, purplish-red, and yellow intraformational mudclasts, with lengths that rarely exceed 10 cm, eroded from adjacent flood plain units, are widespread in the Citronelle.

Cylindrical structures, probably first described in Louisiana, were suggested to be tree root casts formed in "Citronelle soils" (Mossa and others, 1989; Mossa and Schumacher, 1993). Common in St. Helena and St. Tammany Parish exposures, they also occur in Mississippi (Site HAR-19, Location 7 in Figure 1b) and northwestern Florida (e.g., Sites WASH 1 and 2, Locations 17-18; Site H-1 at Location 8, Figure 1d). With maximum diameters ranging from 45 to 100 cm, they often were found in clusters (Figures 10a, b). Suggesting formation by infiltration of sandy muds to gradually replace woody tissues of decomposing tree trunks and roots in wetland settings, the concentric interior structures vaguely resemble tree rings. *In-situ* burial of tree trunks and roots, followed by postdepositional chemical and physical effects initially preserved these features in the surrounding flood plain deposits. Although pedogenic impact in sediments in and around cylinders at shallow subsurface depths continued to influence sediments associated with cylinders still buried, cast-initiating processes were decisive during Citronelle deposition. Unrelated to cylinder formation, this time frame

Figure 7a. Shallow, 18-m wide fluvial channel in thick sandy-gravelly deposits of Site STO-2 (Location 4 in Figure 1b). Scale: person in center-right.

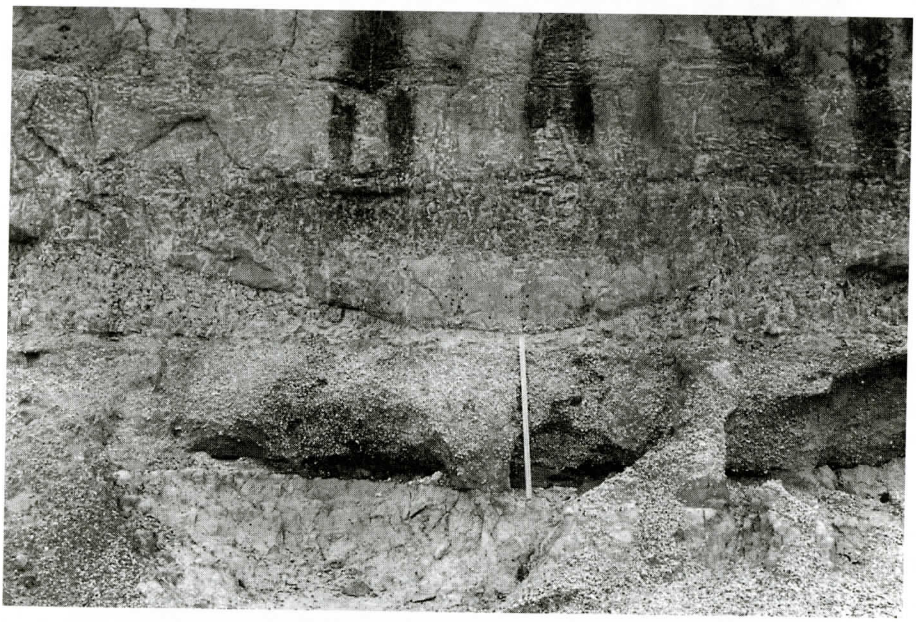


Figure 7b. Small mud- and sand-filled channels, cut in mud-clay lenses. Length of ruler: 91.5 cm. (Site Ea-9, Location 8 in Figure 1c).

applies to a somewhat similar process, the extensive mobilization and precipitation of banded and lenticular iron oxide/hydroxide matter in cross-stratified Citronelle sands (Figures 5, 6).

Following their early development, the outer rims of the cylinders become case-hardened by dehydration of the enclosed mud and the hardening of soft, finely dispersed limonitic matter in the floor of abandoned sand pits and roadcuts. With slow erosional removal of their overburden, these features become steadily more recognizable. The surrounding, softer, less resistant sediment layers are stripped away by differential erosion. Hardening cylinder structures then emerge gradually in the surface. Significant but inconsistent and yet unexplainable contrasts between the size fractions of the interior and the exterior rings were documented in four Louisiana cylinder structures.

Site M-65 (Location 4; Figure 1c) displays

Figure 8. Laminated moderate-grayish yellow flood plain pond mud sequence. Slump folds near top. Overlain by orange sand with abundant white mudclasts. Length of pad: 40 cm. (Site M-19, Location 2; Figure 1c)

Figure 9. Gravel bar deposits top dark purple and light gray mudclast lenses. Syndepositional intrusion of matrix-supported gravel lens into a 40-cm long intraformational clay clast. Visible length of ruler: 33 cm.(Site STO-3, Location 4 in Figure 1b).

the cyclic interlayering between numerous, 12 to 22 cm thick strata. Reflecting the influx of sandier stream flood deposits into muddy flood plain lakes, yellowish-gray, very pale-orange, very fine sand layers alternate with moderate-to-dark reddish-orange mud and muddy fine sand layers. Non-cyclic alternation of flood plain and stream deposits were observed at Site JACK-1 (Location 8, Figure 1b). Cross-stratified and finely laminated fluvial silty fine sand and coarse sand layers are intercalated with three 10 to 80 cm thick, finely laminated, purple clay and mud beds in the 4-5 m thick sequence.

Numerous elongated (10-20 cm) pipe-shaped structures, of 1-3-cm external diameters were found exposed in vertical (growth) position or lying scattered on the pit floor. Composed of hardened muddy sand, they display yellowish-brown, knobby, rough surfaces with very short, stubby branches. These external molds formed around plant roots and stalks. Similar to most cylinder structures, the limonite-cemented molds formed in flood plain deposits, became case-hardened; coming to light during the exhumation process.

Due to the decomposition of organic matter, only few scattered sites (e.g. Site J-2, Location 9, Figure 1d; Site STO-2, Location 4, Figure 1b) retained 10-to-90-cm thick carbonized plant-bearing, very rare muddy-peaty marsh lenses. One such exposure provided the pollen that also confirmed the Formation's Pliocene age (Otvos, 1997, 1998).

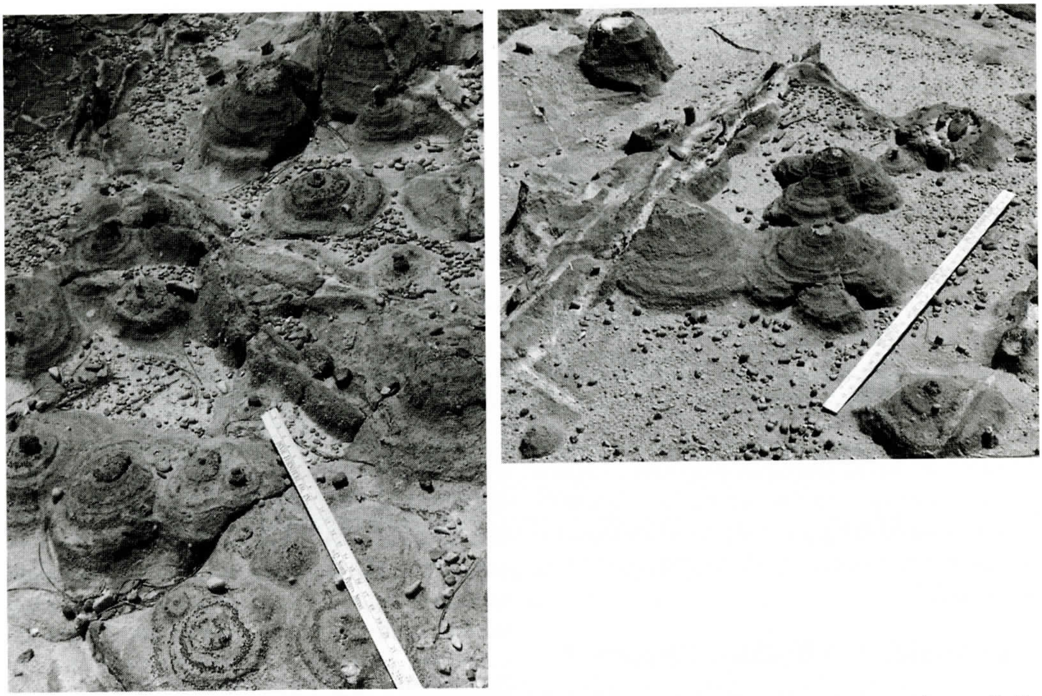
Deposition In Braided Streams?

Rosen (1969), Smith and Meylan (1983), and Self (1983, 1986) regarded the abundance of coarse clastic sediments and the scarcity or absence of fine-textured flood plain deposits as evidence for the braided nature of Citronelle streams. Braided streams are broad and shallow, characterized by extremely variable discharge and choked by bedload. Muddy lithosomes comprise a very small percentage of braided-stream deposits. The laminated sand, silt, and mud facies in braided streams are typically a few centimeters to a few decimeters thick (Miall, 1977). Only three of 41 Red Bluff samples (SE of Location #1, Figure 1b) contained slightly more than 3.5% mud. Smith and Meylan (1983) considered the abundant kaolinitic-illitic intraformational "rip-up" clasts, scattered throughout the sandy Red Bluff sequence as having been reworked from compacted mud that accumulated in abandoned braid channels.

Although sampling in this investigation was constrained and biased by the usually high sand and gravel content in Citronelle borrow pits and by differences in outcrop conditions and sediment variety, mud-enriched sandy deposits and sandy muds were well represented at numerous sites. The frequency of muddy sand, sandy mud, pure mud and clay beds and the prevalence of intraformational mudclasts of a wide size range, consistency and color in many borrow pits imply the existence of substantial muddy Citronelle flood plains throughout the formation's distribution area. Erosion of semi-consolidated mud beds in the stream banks generated large, angular intraformational clay clasts (Figure 9) that experienced minimal reworking and fluvial transport prior to burial in sandy-gravelly river channels. Isolated channels of non-braided streams, extensive lakes, and other fine-textured flood plain-overbank facies were among the probable mudclast sources. Mudclasts are scattered throughout massive sand-gravel intervals in the Wiggins-Pearlington area, south-central Mississippi. Gravelly sand intervals that may not include abundant mudclasts do also occur adjacent to substantial muddy sand sequences (Figure 4a). This indicates the spatial proximity between muddy flood plain deposits and occasionally thick channel gravel and sand intervals.

Estuarine Depositional Environments

Marsh (1966) was the first to identify brackish facies in the Citronelle. *Ophiomorpha* burrow tubes maximum 1.5 m long, formed by callianassid shrimp, are its most common, often only indicators (Figure 11). Approximately a dozen additional sites, display maximum 7 m thick estuarine intervals east of Mobile Bay in Alabama and northwest Florida (Otvos, 1998). They include Sites 12,14,15, 17 in Alabama and Sites 2-4, 6, 8, 14-18, and 19 in Florida (Figures 1c, 1d; Otvos, 1998). Site W-1 (Location 14, Figure 1d) also displays polychaete (annelid) worm tubes, burrow traces, and rare molluscan molds. The white and gray kaolinitic tube walls contrast with the dark yellowish-orange or yellowish-brown colors of the enclosing sediments. Four estuarine lithofacies groups, predominantly of very poor to poor sorting values were identified in 74 samples. The first two of these size categories were most common: (a) granular (0.7-1.8%) clayey, coarse-to-very fine sand with ca. 81-89% sand and 8-26% mud



Figures 10a,b Clusters of concentric, pale yellowish-brown cylindrical structures, cut by partially clay-filled orthogonal fracture network in pale pink Citronelle flood plain deposits. Length of ruler: 91. 5 cm. Site H-1 (Location 8 in Figure 1d).

content; (b) high sand content (ca. 88-98%) with 0-0.9% granule content; (c) dominantly sandy facies with high (ca. 5-44%) granule and gravel content, including sizable gravel clasts; (d) dominantly sandy facies with ca. 25-45% mud content and intercalated mud and clay layers (Figure 2).

The granulometric characteristics of most tube-bearing sediments are indistinguishable from the sandy-muddy alluvial lithosomes. A unique, fifth lithotype at Site Ef-9 (Location 2 in Figure 1d), consists of a moderately well sorted, laminated white sand body, exposed adjacent to clean, tube-bearing sands. This apparently higher energy facies may represent a subtidal sand bar or beach near a Gulf inlet.

Due to diagenetic dissolution, no microfossils were recovered from muddy-clayey lithofacies to confirm paralic and/or marine derivation of these lithosomes. However, a portion of the suspended sediments undoubtedly originated in the Gulf and transported to the estuaries by flood-tidal currents. Judging from their dominantly coarse clastic lithology, the predominant portion of the tube-bearing sands was probably derived from fluvial bedload and suspension load. Cylinder clusters at Site H-1 (Location 8, Figures 1 d and 10 a, b) and other locations may be relicts of brackish arboreal vegetation, rooted in estuarine mud; possible remnants of estuary-fringing mangrove trees. The borrow pit at this site exposes *Ophiomorpha*-bearing intervals with several intercalated fossil-free clay beds that may also be of estuarine origin.

The thickness, the high inland positions and elevations of these estuarine parcels provide an additional proof not only for their prolonged uplift but for deposition during an extended transgression, compatible with late Pliocene data but not with known relatively lower early Pleistocene interglacial sea-levels and associated transgressions (Huddlestun, 1988).

Existence of a Post-Citronelle Cover Unit

The sharp contrast between the Citronelle and the overlying 1-3 m thick pale yellow sandy

Table 2. Clay mineral content in percentages, listed by outcrop sites, related to location group numbers (Site locations, in Appendix). Analyses by D. A. Darby.

	kaolinite	halloysite	illite	smectite	chlorite (chamosite)
Baldwin County, AL (Locations 12, 14; Fig.1c)					
B-6, s. 4	80	-	20	-	-
B-57 s.3, Site	3	83	14	-	-
Holmes County, FL (Location 8; Fig. 1d)					
H-1, Group A, Loc.	81	-	19	13	-
Jackson County, FL (Location 9; Fig. 1d)					
JF-2, Site	30	58	12	-	-
Mobile County, AL (Location 2; Fig. 1c)					
M-19, Site	89	-	11	-	-
—21, s.2	amorphous, noncrystalline clay matter				
M-50a s.2	84	-	16	-	-
M-50	74	-	26	-	-
St. Helena Parish, LA (Location 2; Fig. 1a)					
ST. HEL-2, s. 2	92	-	8	-	-
Stone County, MS (Locations 4, 5; Fig. 1b)					
STO-1(Dyess Pit NE)	64	-	36	-	-
STO-2 (Dyess Pit)	c.54	-	46	-	-
STO-3 (Perkin-ston Pit), s.8	19	-	63	13	-
STO- 6 (Perkin-ston Pit) s.6	34	-	44	-	-
Walton County, FL (Location 14; Fig. 1d)					
WALT-1, s.11 (Mossy Head)	100	-	-	-	-
Washington County, FL (Locations 18, 20; Fig.1d)					
WASH-2 s. 3	97	-	3	-	-
WASH-2 Group F, s.1	50	-	0.4	trace	49
WASH-4, s. 100b (fracture-fill)	100	-	-	-	-

Figure 11. Callianassid *Ophiomorpha* (ghost shrimp) burrow tube traces in moderate yellowish-brown estuarine deposits, Pit W 4 (Location 15 in Figure 1d). Visible length of ruler: 47 cm.

Figure 12. Orthogonal and cross-cutting sets of white kaolinitic clay-filled fractures exposed in light brown, pale reddish-brown pit floor. Length of ruler: 91.5 cm. Site H-1 (Location 8 in Figure 1d).

deposits that blanket the formation mostly east of Mobile Bay suggest that this 1-3-m-thick "cover sand" interval was not simply the leached pedogenic alteration product of top sandy Citronelle beds. Redeposition by eolian and slopewash processes may explain the origins of this widespread unit. Cylindrical structures were absent from these cover deposits, luminescence-dated at two locations as 66 and 37 ka BP (Otvos, 2004).

Recurring Quaternary aridity episodes resulted in deflation and dune ridge construction on adjacent Pleistocene coastal plain. The hundreds of blowout depressions that dot the Citronelle surface (Otvos, 1976) point to potential eolian "cover sand" sources. Two luminescence dates obtained from "cover sand" samples place that interval in the Wisconsin glacial stage. Unlike the SE Alabama and NW Florida Pleistocene coastal plain, occupied by eolian sandsheets and ridges (Otvos, 2004), the Citronelle surface is devoid of Quaternary dunes.

Tectonic Influences

An alluvial sequence at Site WASH-4 (Figure 4b; Location 20 of Figure 1d), capped by the gently Gulfward inclined regional Citronelle surface suggests localized tectonic activity prior to more recent Citronelle alluviation. The unusually steep, uniform 30°-to-40° coastward inclination of this parallel-layered ca.16-m thick interval in a large borrow pit is not compatible with deposition in a fluvial bar setting or in a deep steep-walled valley, entrenched during a hypothetical non-depositional intervals. Individual beds in such instances would display significant variations in strike and dip values.

The 180 m + elevation of the Citronelle in central Mississippi (Boswell, 1979) reflects updip-increasing substantial post-Pliocene coastal plain uplift that increases landward of the hinge zone. The hinge zone concept was first enunciated by Fisk (1944) in Louisiana. Faulting-related terrace scarps and previously unreported clay-filled orthogonal fracture networks (Figures 10a, b, 12; Site H-1,Table 2), were also related to post- Citronelle tectonic impact. The coastal stream net pattern, faulting, and other fracture-related surface lineaments, including scarps of structural origin commonly indicate tectonic influences, universally imprinted in the northern Gulf Pliocene and Quaternary coastal surfaces (Otvos, 1981, 1991, 1997; Self, 1986; Snead and McCulloh, 1984; Heinrich, 2000; McCulloh, 2003). Detailed field and subsurface studies will be required to reconstruct the tectonic evolution of the Citronelle plain.

CONCLUSIONS - THE SEARCH FOR FLUVIAL MODELS

Large-scale cross strata formed in channel bar and subaqueous dune settings alone do not conclusively prove the *braided* channel style of most or all Citronelle paleo-streams. While steeper valley gradients, more variable discharge, and higher level of unit stream power may play roles in defining braided stream patterns *vs.* meandering ones (Knighton 1998;Bridge, 2003; Leigh et al., 2004), the volume and caliber of bedload and presence of readily erodible stream banks appear to be usually the critical conditions in braidplain development.

Self (1986) who supports the essentially braided river origin of the Citronelle paleostreams, documented a 12-15 m thick silt-clay intervals that adjoin thick sand-gravel sequences, similar to those encountered in the large borrow pits of south Mississippi. The very frequent heterolithic and muddy intervals encountered in and adjacent to coarse clastic lithosomes suggest the role of flood plain sedimentation. Absence of readily recognizable meander point bars with a characteristic vertical trend in dip parameters and upward-decreasing median grain size (Miall, 1996) may be linked to the lack of good quality exposures, usually manifested by limited lateral continuity. This absence does not necessarily preclude the possibility that meandering and other non-braided streams were important agents in flood plain deposition.

Meanderbelt migration, avulsion, and cutoff processes generally create and preserve a large array of inactive meanderplain channels, filled by muddy and clayey sediments. In contrast, in the absence of comparable lateral shifts of the active streamplain and due to their greater channel widths, braided streams are more likely than meandering ones to erode and remove the bulk of previously accumulated muddy channel-fillings and other fine-grained flood plain deposits.

For lack of extensive outcrops to provide conclusive sedimentary evidence for variable fluvial styles, of braided and/or meandering paleostreams, it is probable that accumulation of Citronelle alluvium involved different fluvial styles in the different drainage basins at different times. Judging from the size range of incorporated clastic sediments, *gravel-wandering, gravel-sand-meandering, gravel- meandering,* and *wandering* rivers (Miall, 1996) may have also participated in Citronelle alluviation. Some of the non-braided stream categories produced only very limited volumes of flood plain fines.The fine-textured and well-dated allluvial Miccosukee facies of the Citronelle Formation east of the Apalachicola River in part may have accumulated in meanderplains (Otvos, 1998). Originally, Huddlestun (1988) regarded the alluvial-paralic Miccosukee as a separate formation, correlative of and coeval with the Citronelle. Considering the widespread inclusion of muddy intervals, low- and high-sinuosity anastomosed, and intermediate meandering-braided streams may have played a significant role in Citronelle deposition.

In order to facilitate paleogeographic reconstruction of the ancient stream basins and associated estuarine shorelines, comprehensive and detailed studies would be desirable in the future. Ideally, such investigations would document various types of depositional styles and fluvial architecture and map individual watersheds with associated paleo-stream nets across the Citronelle distribution area.

ACKNOWLEDGMENTS

Dennis A. Darby performed the clay analyses. Sincere thanks are due to Dr. Marco J. Giardino and NASA's Commercial Application Directorate for encouragement, financial and material support in this multi-year project. Expert graphic designers Messrs. Kevin Eckhoff and Shannon Ellis of Lockheed-Martin, Stennis SC Operations, prepared electronic illustration files of high quality. Help provided by Wade E. Howat and Howard J. Newby over many years in the field and laboratory work was also deeply appreciated. Thanks for the highly constructive and detailed reviews are due to Mr. Richard P. McCulloh and Dr. Robert Self; for generous assistance with the completed manuscript and illustrations, to Editor Dr. Duncan Heron.

REFERENCES

Boswell, E. H., 1979, The Citronelle Aquifer in Mississippi: U.S. Geological Survey Water Resources Investigations Open File Report No. 78-131. One sheet.

Bridge, J. S., 2003, Rivers and Floodplains: Forms, Processes, and Sedimentology. Blackwell Publ., Oxford, 491 pp.

Fisk, H. N., 1944, Geological investigation of the alluvial valley of the lower Mississippi River: Vicksburg, Mississippi. U.S. Army Corps of Engineers, 78 p., with plates.

Folk, R., 1961, Petrology of Sedimentary Rocks, 152 p., The University of Texas. Hemphill's, Austin, Texas.

Heinrich, P. V., 2000, De Quincy fault-line scarp, Beauregard and Calcasieu Parishes, Louisiana: Louisiana Geological Survey Basin Research Institute Bulletin, v.9, p. 38-50.

Huddlestun, P. F., 1988. The Miocene through Holocene. A revision of the lithostratigraphic units of the coastal plain of Georgia: Georgia Geological Survey Bulletin, No. 104, 162 p.

Isphording, W. C., 1976, Multivariate mineral analysis of Miocene-Pliocene coastal plain sediments: Transactions Gulf Coast Association Geological Societies, v. 26, p. 326-331.

Isphording, W. C. and Flowers, G., 1983, Differentiation of unfossiliferous clastic sediments: sections from southern portion of the Alabama-Mississippi coastal plain: Tulane Studies in Geology and Paleontology, v. 17, p. 59-83.

Knighton, D., 1998, Fluvial Forms and Processes: A New Perspective. Arnold, London, 383 pp.

Leigh, D., Srivastava, P., and Brook, G. A., 2004, Late Pleistocene braided rivers of the Atlantic coastal plain, USA: Quaternary Science Reviews, v. 23, p. 65-84.

Marsh, O. T., 1966, Geology of Escambia and Santa Rosa Counties, western Florida Panhandle: Florida Geological Survey Bulletin, v. 46, 140 p.

Matson, G. C., 1916, The Pliocene Citronelle Formation of the Gulf Coastal Plain: U.S. Geological Survey Professional Paper 98, p. 167-192.

McCulloh, R. P., 2003, The stream net as an indicator of cryptic systematic fracturing in Louisiana: Southeastern Geology, v. 42, p. 1-17.

Miall, A. D., 1977, A review of the braided-river depositional environment: Earth-Science Reviews, 13, p.1-62.

Miall, A. D., 1996, The Geology of Fluvial Deposits, 582 p., Springer.

Mossa, J., B. J. Miller, and G. Kellner, 1989, Site 4 The Cylinders, p. 41-44 in: Quaternary Geomorphology and Stratigraphy of the Florida Parishes, Southeastern Louisiana, J. Mossa and W. J. Autin, Editors. Louisiana Geological Survey Guidebook Series No. 5, 98 p.

Mossa, J. and Schumacher, B. A., 1993, Fossil tree casts in south Louisiana soil: Journal of Sedimentary Petrology, v. 63, p. 707-713.

Otvos, E. G., 1976, Pseudokarst and psedokarst terrains-basic problems of terminology: Geological Society of America Bulletin, v. 87, p. 1021-1027.

Otvos, E. G., 1981, Tectonic lineaments or Pliocene and Quaternary shorelines, northeast Gulf Coast: Geology, v. 9, p. 398-404.

Otvos, E. G., 1991, Houston Ridge, SW Louisiana - end link in the Late Pleistocene Ingleside barrier chain? Prairie Formation newly defined: Southeastern Geology, v. 31,

p. 235-249.

Otvos, E. G., 1997, Northeastern Gulf Coastal Plain Revisited. Neogene and Quaternary Units and Events- Old and New Concepts: Gulf Coast Association of Geological Societies and New Orleans Geological Society, 143 p.

Otvos, E. G., 1998, Citronelle Formation, northeastern Gulf Coastal Plain: Pliocene stratigraphic framework and age issues: Transactions Gulf Coast Association Geological Societies, v. 48, p.321-333.

Otvos, E. G. 2004, Prospects for interregional correlations using Wisconsin and early Holocene aridity episodes, northern Gulf of Mexico Coastal Plain: Quaternary Research, v. 61, p.105-118.

Rosen, N., 1969, Heavy minerals and size analysis of the Citronelle Formation of the Gulf Coastal Plain: Journal Sedimentary Petrology, v. 39, p. 1552-1565.

Self, R.P., 1983, Petrologic variation in Pliocene to Quaternary gravels of southeastern Louisiana: Transactions Gulf Coast Association Geological Societies, v. 33, p. 407-415.

Self, R. P., 1986, Depositional environments and gravel distribution in the Plio-Pleistocene Citronelle Formation of southeastern Louisiana: Transactions Gulf Coast Association of Geological Societies, v. 36, p. 561-573.

Shlemon, R. J., 1995, written comm. Roy Shlemon and Associates, Newport Beach, CA.

Smith, M. and Meylan, M. A., 1983, Red Bluff, Marion County, Mississippi: A Citronelle braided stream deposit: Transactions Gulf Coast Association Geological Societies, v. 43, p. 419-432.

Snead, J. I. and McCulloh, R. P., 1984, Geologic map of Louisiana: Louisiana Geological Survey. Scale: 1:500,000.

Torrent, J., Nettleton, W. D. and Borst, G., 1980, Clay illuviation and lamella formation in a psammentic Haploxeralf in southern California: Soil Science Society of America Journal, v. 44, p. 363-369.

APPENDIX

See following pages.

APPENDIX

Note: Location of all studied Citronelle samples, including cited locations of estuarine deposits, cylinder structure locations, and "cover sands:. Mud content: average mud percentage per site of Citronelle floodplain sediments, based on number of samples in brackets. (Sediment composition of "cover sands" and estuarine deposits were excluded.)

Sample Location				
Location number by map county/parish	**Site designation**	**Location by sec.-R.-T.**	**USGS Quadrangle**	**average mud content, in %; sample number**
SOUTHEAST LOUISIANA (Figure 1a)				
St. Helena				
2	Outcrops along Highways 37/449; 441/38; 73-2S-4E; 46-1S-5E; 32-2S-6E; 4-3S-6E		Greensburg Felixville	52.8 (16)
3	Greensburg Outcrop	15-3S-5E	Greensburg	cylinders, in reference
Tangipahoa				
1	Kentwood Pit	20-1S-7E	Kentwood	53.7 (10)
4	Pit T-1 (Bolivar)	14-2S-8E/7E	Chesbrough	83.0 (20)
5	Pit T-2 (Wilmer)	5-3S-9E; 38-2S-7E	Wilmer (Mt.Hermon)	68.8 (4)
MISSISSIPPI (Figure 1b)				
Lawrence				
1	LAW-1 (Tilton Pit)	18-5N-12E	Tilton	26.5 (5)
Covington				
2	COV-1 (Kola Pit)	n/a	Collins	19.8 (18)
	COV-2-through- COV-5	n/a	Collins	
Forrest				
1	FOR-1 (Hoover Pit)	n/a	Hattiesburg SW	54.6 (3)
2	FOR-2 (Leesville Pit)	n/a	Hattiesburg	2.8 (1)
Stone				
4	STO-1 (Dyess Pit #1)	1/2-3S-13W	Browns Lake	22.8 (41)
	STO-2 (Dyess Pit #2)	12-3S-13W	dto	
	STO-3 (Dedeaux Pit-W)	10-3S-12W	Wiggins	
5	STO-4 (Dedeaux Pit-E)	28-3S-11W	Wiggins	30.5 (17)
	STO-5 (City Bridge Rd Pit)	26-3S-11W	Whites Crossing	
	STO-6 (TV Antenna Pit)	35-3S-11W	Airey	
Harrison				
6	HAR-1(RVA Pit, E of Hwy 49)	3-4S-11W	McHenry	26.4 (13)
	HAR-25 (Edwards Pit)	14/23-4/5S-11W	McHenry	
7	HAR-19 (Ollie Lamey Pit)	26-6S-10W	Biloxi	49.7 (5)
7a	HAR-23 (Baughn Pit)	25-6S-10W	Biloxi	15.6 (6)
Jackson				
8	JACKS-1 (Russell Pit)	28-6S-7W	Gautier-N	58.4 (16)
ALABAMA (Figure 1c)				
Mobile				
1	M-42	28-1N-2W	Citronelle-E	6.6 (2)
2	M-4 (Brownlee Paving Pit)	15-3S-2W	Kushla	52.0 (48)
	M-19 (HMR Construct)	24/25-2S-2W	Kushla	
	M-21 (Jarrett Road Land-fill)	22–3S-2W	Kushla	
	M-32 (Pritchard Pit)	28-3S-2W	Kushla	
	M-33 (L&J Dirt, Inc.Pit)	17-3S-2W	Kushla	
	M-35 (M+S Pit)	17-3S-2W	Kushla	
	M-39 (F.Overstreet Pit)	17-3S-2W	Kushla	
	M-50 (Pentecostal Ch.)	29-2S-2W	Kushla	
	M-50/a (Mauvilla Track)	28-2S-2W	Kushla	
	M-54 (Southside Storage Inc. Pit)	22-3S-2W	Kushla	
3	M-24 (Weaver Pit)	10-4S-3W	Tanner Williams	27.9 (16)

	M-40 (Weaver Pit)	10-4S-3W	Tanner W.	
	M-49 (OL Pit)	10-4S-3W	Tanner W.	
4	M-60 (Wolf Ridge Rd Pit)	36-3S-2W	Spring Hill	32.8 (19)
	M-65 (Schillinger/ Cottage Hill Rds)	6-5S-2W	Spring Hill	
	M-66 (Boykin Landfill)	6-5S-2W	Spring Hill	0.9 (5)
5	M-10 (Dirt Inc. Pit)	6-6S-2W	Theodore	34.1 (68)
	M-13	5-6S-2W	Theodore	
	M-15 (Esfeller/Gibson Roads)	19-6S-2W	Theodore	
	M-16 (Esfeller Pit, Hwy 90)	19-6S-2W	Theodore	
	M-57 (Old Pascagoula Road)	32-5S-2W	Theodore	
	M-59 (Ward Landfill Pit)	32-5S-2W	Theodore	
6	M-64 (Risley Pit)	3&4-7S-4W	Kreole	67.5 (2)
3	cores from six drillholes	16/17-4S-3W	Tanner W.	24.1 (64)
Escambia				
7	Ea-23(Staley&Smith Pit)	5-1N-6E	Atmore	49.1 (18)
	Ea-23b (Sizemore Creek)	5-1N-6E	Atmore	
8	Ea-1 (railroad cut)	26-1N-8E	Pollard	54.3 (15)
	Ea-9 (Ch. Fore Pit)	16-1N-8E	Flomaton	
9	Ea–4 (Campbell Pit)	30-1N-9E	Flomaton	9.8 (3)
Baldwin				
10	B-64 (Jim Earle Pit)	7-5S-2E	Bridgehead	2.5 (2)
11	BO-1(Red Gully, Hway 98)	29-5S-2E	Daphne	4.3 (5)
12	B-6 (Jenkins Pit)	20-4S-3E	Stapleton	33.2 (44)
	B-14 (Darby Pit, N wall)	8-4S-3E	Stapleton	
	B-51 (Malbis-E Pit)	26-4S-2E	Stapleton	
13	B-33a (Brantley Pit)	21-5S-2E	Daphne	16.9 (24)
	B-42 (Corte Pit)	28-5S-2E	Silverhill	
	B-45 (J. Stapleton Co. Pit)	16/17-5S-2E	Silverhill	
	B-46 (McBride Pit)	16-5S-3E	Silverhill	
14	B-15 (Ideal Dirt Pit)	33-6S-3E	Magnolia Spr.	33.7 (22)
	B-23 (Hway 27 Pit)	11-6S-2E	Magnolia Spr.	
	B-57 (N&S Millers Pit)	32-6S-3E	Magnolia Spr.	
	B-62 (Wiley Pit)	27-6S-2E	Magnolia Spr.	
	B-63 (Wiley Pit)	27-6S-2E	Magnolia Spr.	
15	B-4 (H. Weaver Pit)	13/24-6S-3E	Robrtsdale SW	21.9 (5)
16	B-31 (Kelly Pit)	26-7S-3E	Foley	27.9 (12)
	B-32 (Layco Mining Pit)	19-7S-3E	Foley	
	B-53 (Tempco Pit)	35-7S-3E	Foley	
17	B-1 (Fell Pit)	15-7S-6E	Lillian	22.9 (7)
	B-2 (GFD Pit)	23-7S-6E	Lillian	
	B-3 (McDirt Pit)	15-7S-6E	Lillian	
	B-18 (Rosalie Rd)	27-7S-6E	Lillian	
18	BO-2 (Red Bluff on Perdido Bay)	16-8S-32W	Perdido Bay	34.8 (7)
FLORIDA (Figure 1d)				
Escambia				
1	Ef-3, roadcut	35-1N-31W	Cantonment	62.5 (2)
2	Ef-1 (Chadbourne Pit)	24-1S-30W	W.Pensacola	19.0 (54)
	Ef-2 (Clark Pit)	38-1S-31W	W.Pensacola	
	Ef-4 (Green Pit)	25-1S-30W	W.Pensacola	
	Ef-5 (Gorden Pit, American Clay Co.)	42/43-1S-30W	W.Pensacola	
	Ef-6 (Heaton Pit)	27-1S-13W	W.Pensacola	
	Ef-7 (McDirt Pit)	38-1S-31W	W.Pensacola	
	Ef-8 (Rolling Hill Landfill)	40-1S-30W	W. Pensacola	
	Ef-9 (Landfill-2)	40-1S-30W	W. Pensacola	

3	Escambia Bay bluffs	1&2-2S-29W	Pensacola	28.7 (30)
Gadsden				
4	GAD-1	7-2N-6W	Rock Bluff/ Sycamore	only estuarine
5	GAD-3	26-3N-3W	Dogwood, FL-GA	54.9 (9)
	GAD-3a	35-3N-3W	Quincy	
6	GAD-2 (County Pit)	28-3N-6W	Sycamore-Chattahootchee, FL - GA	15.6 (12)
7	GAD-4	59-1N-4W	Bloxham	4.2 (8)
	GAD-5	50-1N-4W	Bloxham	
Holmes				
8	H-1	27-4N-17W	Ponce de Leon	49.7 (15)
Jackson				
9	Jf-1(Poplar Springs Ch.)	9-4N-9W	Marianna	36.9 (17)
	Jf-2	8-4N-9W	Marianna	
	Jf-3	16-5N-9W	Marianna	
10	Jf-5	12-4N-11W	Cottondale	42.9 (2)
	Jf-6	14-4N-11W	Cottondale	
Leon				
11	Ln-1	6-1S-2W	Midway	16.1 (16)
	Ln-2 (Allen Pit)	6-1S-2W	Midway-Tallahassee	
	Ln-3	34-1N-2W	Midway	
	Ln-4 (Peevey Pit)	36-1N-2W	Midway	
	Ln-5 (Roberts Pit)	35-1N-2W	Midway	
	Ln-6 (Solomon Pit)	34-1N-2W	Midway	
Liberty				
12	Ll-1 (Brent Mngment Area)	29-1N-3W	Bristol	5.8 (1)
4	Ll-2	12-2N-7W	Rock Bluff	46.7 (7)
	Ll-3 (St. Joseph Paper Co.)	23-2N-7W	Rock Bluff	
Santa Rosa				
13	SR-1 (Russell Pit, Milton)	20-11N-28W	Milton-S	2.1 (5)
	SR-2 (Robertson Pit, Milton)	28-11N-28W	Milton-S	
Walton				
14	W-1(Mossy Head Pit)	21-3N-21W	Mossy Head	25.4 (13)
15	W-2 (Woodyard Rd Pit)	32-3N-19W	DeFuniak Springs-W	20.5 (20)
	W-3 (Boy Scout Camp Rd)	23-3N-20W	DeFun.Sprs-W	
	W-4 (Boy Scout Camp)	25-3N-20W	DeFun.Sprs-W	
	W-5 (Millard Gry. Rd Pit)	9-2N-19W	DeFun.Sprs-W	
	W-6	15-2N-19W	DeFun.Spr.-W	
16	W-7 (Argyle Pit)	28/29-3N-18W	DeFuniak Springs-E	30.5 (5)
Washington				
17	Outcrop 1 (Oswald Rd)	18-4N-13W	Chipley	58.0 (8)
	Outcrop-2 (Bahomia Rd)	26-5N-13W	Chipley	
	WASH-1	13-4N-14W	Chipley	
18	WASH-2	18-3N-12/13W	Wausau	32.5 (33)
	WASH-6	18-3N-13W	Wausau	
19	WASH-3 (N of Fire Tower)	12-2N-14W	Gap Lake	12.4 (3)
	WASH-5 (Old Jenkins Pit)	7-2N-13W	Gap Lake	
20	WASH-4 (Highway 279)	30-4N-15W	Hinsons Crossroads	26.9(29)

SOUTHEASTERN GEOLOGY
V. 43, No. 1, August 2004, p. 21-38

MIDDLE CAMBRIAN POLYMEROID TRILOBITES AND CORRELATION OF THE CAROLINA AND AUGUSTA TERRANES

M. A. S. MCMENAMIN

Department of Earth and Environment
Mount Holyoke College
South Hadley, MA 01075

P. G. WEAVER

North Carolina State Museum of Natural Sciences
11 West Jones Street
Raleigh, NC 27601

ABSTRACT

Cambrian polymeroid trilobites permit, for the first time, biostratigraphic correlation between the Carolina Slate Belt (Carolina terrane) and Belair Belt (Augusta terrane) of Georgia and North and South Carolina. An unnamed trilobite with an unusually wide thorax and an upturned anterior cranidial border (ptychoparioid genus and species A) allows correlation between the two belts at or near the stratigraphic level defined by the *Tomagnostus fissus-Ptychagnostus atavus* and *Eccaparadoxides eteminicus-Triplagnostus gibbus* biozones.

Biostratigraphic and lithostratigraphic correlations support the concept that the Belair Belt and Carolina Slate belt were once contiguous, in accord with the hypothesis of Shervais and others (1996) that the Augusta terrane is a fragment of the Carolina terrane caught in the hanging wall of the Augusta fault.

A new paradoxidid species (*Paradoxides (Acadoparadoxides) grandoculus* n. sp.) is described here from the Batesburg fauna. *Eccaparadoxides eteminicus*, newly recognized here from South Carolina, provides a biostratigraphic and paleobiogeographic link to Avalonian terranes in New Brunswick and Newfoundland. Conocoryphid trilobites are reported here for the first time from Batesburg. *Skehanos* sp. and *Braintreella* sp., also present at Batesburg, demonstrate paleobiogeographic linkages to a somewhat older Avalonian fauna from the Massachusetts terrane. Thus a single Avalonian biogeographic province of Middle Cambrian age may be identified in the Americas as extending from eastern Newfoundland to eastern Georgia, confirming the lithotectonic correlations between the South Carolina Piedmont and the Avalon Peninsula in Newfoundland proposed by Williams and Hatcher (1982). Middle Cambrian faunal similarities with Baltica, Bohemia and Armorica (France) underscore the extent of the Avalonian biogeographic province. Avalonia appears to have been an extensive island arc or archipelago associated with a huge subduction zone.

INTRODUCTION

Paradoxidid trilobites of the "Atlantic province" (now referred to as Avalonia) provided critical evidence in support of the concept that ocean basins open and close over geologic time (Wilson, 1966). On the western side of the Atlantic, Cambrian trilobites of Avalonia are known to occur from Georgia to Newfoundland.

The first Cambrian trilobite discovery in the Piedmont region of the southeastern United States was made the late 1970's near Augusta, Georgia. The discovery was made in the Belair Belt, a region of felsic to intermediate metatuffs and metasediments separated from the Carolina Slate Belt by both the Kiokee Belt and by the Augusta fault zone (Maher and others, 1981). This enigmatic fossil, consisting of a thoracic region of 16-17 segments, lacked both cranidium and pygidium, but nevertheless helped to constrain the age of the Belair Belt strata to Middle Cambrian-Ordovician (Maher and others, 1981). Based on the presence of numerous and relatively uniform thoracic segments, Maher and others (1981) compared the fossil to Ordovician trilobites of the family Pliomeridae. The comparison could not be carried further due to the incompleteness of the specimen. It is the only fossil specimen known from the Augusta terrane.

Abundant Middle Cambrian trilobites discovered in 1982 by Sara L. Samson near Batesburg, South Carolina provided evidence that the Carolina Slate Belt was an exotic terrane (Secor and others, 1983; Samson, 1984; Samson and others, 1990). The discovery specimen (a paradoxidid glabella) was found in March 1982 as Samson bent down to tie a shoelace during a geological mapping exercise (Samson, 1984, p. 1-2).

The Euro-African faunal affinities of these and associated fossils provide important clues for the assessment of Proterozoic-Cambrian tectonic arrangements (Samson and others, 1990, their Table 2; Hatcher, 2000; McMenamin and Weaver, 2002). The tectonic setting of Avalonian terranes has been characterized as a rifted-arc environment associated with episodic subduction and associated magmatism during the prolonged breakup of Rodinia (Murphy, 2002). The paleobiogeographic positions of Avalonian terranes may help to clarify the sequence of convergent tectonic events that led to the amalgamation of Gondwana. Current models place the Avalonian terranes close to Baltica, the Amazonian Craton and the West African Craton (Nance and Murphy, 1996; van Staal and others, 1996). These models received strong support from the results of work on detrital zircons from the Emory Formation (Samson and Secor, 1999; Samson and others, 2001; Secor and Snoke, 2002). The near absence of billion year old zircons from the detrital suite suggest that the sediments accumulated far from North America, and the preponderance of zircon ages in the 2.5-1.8 billion year range is interpreted to indicate a western Gondwanan provenance for the deposits (Samson and Secor, 1999; Samson and others, 2001; Secor and Snoke, 2002).

Trilobite fossils from the Carolina Terrane described here help resolve the chronological and paleobiogeographical relationships of the Carolina Slate Belt Middle Cambrian rocks to regions elsewhere. Unresolved questions regarding the Carolina trilobite faunas remain, including: their exact relationship to correlative Avalonian rocks of the northeast, the water depth inhabited by the faunas, and the proximity of the Carolina Terrane to the faunas of the periphery of North America.

The water depth of the fauna is unknown, although the rocks appear to be from a shallower water facies than are the older rocks of the Richtex Formation (an unfossiliferous, presumed turbidite; Secor and Snoke, 2001, their Figure 3). The Carolina trilobites with preserved eyes (particularly the large-eyed paradoxidids) strongly suggest that the fossiliferous sediments formed within the photic zone. The large eyes of the paradoxidids might imply a habitat in the deeper, dimmer parts of the photic zone. Such an inference would be consistent with the associated agnostids that are thought to have preferred open-shelf environments (Briggs and Robison, 1984, their Figure 2).

Samson and others (1990), backing away from their initial interpretations of the Carolina terrane as an exotic terrane (Samson, 1984; Secor and others, 1983), argued that if the fossils were to be interpreted as a deep, cool-water fauna, then they might then have lived along the periphery of North America. If this were to have been the case, the tectonic displacement of the Carolina Terrane relative to North America need not necessarily have been great.

This revised interpretation has led to a divergence in views, with some advocating the deep water hypothesis (thus allowing a considerable paleobiogeographic linkage to the North American craton; Mueller and others, 1996), and others advocating a shallow water habitat for the fauna (based on sedimentological evidence for "very shallow water deposition" in the Asbill Pond formation; Shervais and others, 1996, p. 221). The debate mirrors another controversy over the presumed water depth of deposition in Avalonian strata, this time involving the beds yielding the famous Ediacaran biota of the Conception Group at Mistaken Point, Newfoundland (Peterson and others, 2003). Clapham and Narbonne (2002, p. 629) assert that this Ediacaran biota was deposited in "deep water well below the photic zone," whereas O'Brien and others (1996) note that the tuffaceous sandstones and mudstones that host the Ediacaran fossils are part of a shallowing, and perhaps quite shallow, depositional sequence. Judging from the paleontological evidence alone, the gigantic (120 cm or more in length), unnamed "Christmas tree" Ediacaran fossil at Mistaken Point is sufficiently kelp-like to suggest that at least some light was available during deposition of the Conception Group. Also, actualistic sedimentation models may lead to errors when interpreting Proterozoic depositional environments, and a cautious approach is required when interpreting the water depths of Ediacaran habitats.

Both the South Carolina trilobites and the Newfoundland Ediacarans appear to have been deposited within the photic zone. In the case of South Carolina it would tend to support the original interpretation of the Carolina Slate Belt as an exotic terrane. Indeed, the presence of the Ediacaran *Pteridinium carolinaensis* in the Carolina Slate Belt (McMenamin and Weaver, 2002) suggests that the Proterozoic-Cambrian fossils of the Carolina Terrane and those of autochthonous North America belong to different paleobiogeographic provinces. This contrast supports the notion that Avalonian rocks are indeed exotic and formed some distance (1000 km or more) from the ancient shores of the present-day eastern margin of North America, although some faunal communication with North America cannot be ruled out. A few genera characteristic of the North American craton (*Mickwitzia, Nevadia*) are known from Avalonia.

Soon after the fossil discoveries near Batesburg, Secor and others (1983, their Figure 1) published a correlation between the South Carolina slate belt, Avalonian Massachusetts and other Avalonian terranes to the north. The correlation was based on Middle Cambrian age dates based primarily on agnostid and polymeroid trilobites. Genus and family level similarities were recognized between the trilobites of the two regions, particularly in the paradoxidid trilobites and in trilobites of the ptychoparioid family Agraulidae (Secor and others, 1983; Samson, 1984; Samson and others, 1990).

More faunal similarities were identified by McMenamin and Weaver (2002, their Figure 9) and McMenamin (2002). In particular, the trilobite genera *Paradoxides (Acadoparadoxides)*, *Braintreella* and *Skehanos* are endemic to both the Carolina and Massachusetts terranes.

THE BATESBURG FAUNA

Field studies conducted during July-August 2002 produced new South Carolina trilobite material. Several species of paradoxidids were collected from Locality 1 of Samson and others (1990) from massive blocks of orange-weathering light gray siltstone to fine sandstone. These blocks were relatively unfossiliferous, in contrast to the thinly bedded siltstones nearby that yielded the ptychopariid trilobite *?Conocoryphe* (sp.).

A new faunal list (Table 1) may now be presented for the Batesburg locality. Localities 1 and 6 are from Samson and others (1990). Note that *Hypagnostus parvifrons* is known from Locality 5 of Samson and others (1990), and that ptychoparioid genus and species A is known from Locality 2 of Samson and others (1990).

BIOSTRATIGRAPHY AND PALEOBIOGEOGRAPHY

Samson and others (1990) assigned the Batesburg fauna to the *Ptychagnostus atavus* Zone of the mid-Middle Cambrian. This age determination was based on the presence, at their Locality 6, of the agnostids *Hypagnostus* and *Peronopsis fallax*. As *Hypagnostus* does not range below the *Ptychagnostus atavus* Zone, and *Peronopsis fallax* does not range above this zone, the age of the deposit (at least at Locality 6) was precisely placed at the *Ptychagnostus atavus* Zone, an astonishingly close age determi-

Table 1. Faunal list of Middle Cambrian fossil invertebrates from Batesburg, South Carolina. Modified from Samson and others (1990) and Secor and Snoke (2002). Localities 1 and 6 are from Samson and others (1990). Note that *Hypagnostus parvifrons* is known from Locality 5 of Samson and others (1990), and that the ptychoparioid genus and species A is known from Locality 2 of Samson and others (1990).

	Locality 1	Locality 6
Agnostid Trilobites	x	x
Hypagnostus mammillatus		x
Hypagnostus parvifrons		
Peronopsis cf. *fallax*		x
Ptychagnostus sp.	x	x
Tomagnostus fissus	x	x
Polymeroid Trilobites	x	x
?*Conocoryphe* sp.	x	
Skehanos sp.	x	
?*Agraulos* sp.	x	
Braintreella sp.	x	
?*Skreiaspis* sp.	x	
Paradoxides (*Acadoparadoxides*) *grandoculus* n. sp.	x	x
Eccaparadoxides eteminicus	x	
ptychoparioid genus and species A		
Hyoliths		x

nation considering the limited vertical extent of available biostratigraphic control.

The specimen of *Peronopsis fallax* illustrated by Samson and others (1990, their Figure 5A) seems atypical for the species, as its anteroglabella is elliptical and considerably reduced in size compared to the semicircular anteroglabella seen in *Peronopsis fallax* from western North America (Robison, 1982). As such the species assignment of the Carolina specimen may be questioned. We will thus refer to this specimen as *Peronopsis* cf. *fallax*. On the other hand, Carolina specimens of the agnostid trilobite *Hypagnostus* are confidently assigned to this genus and thus an age for the *Hypagnostus*-bearing part of the Batesburg fauna as no older than the base of the *P. atavus* Zone seems secure.

A case for a slightly older age can be made for the trilobites of Locality 1. The fauna has produced *Eccaparadoxides eteminicus* (= *Paradoxides* cf. *P. eteminicus,* Pl. 4, Figure C in Samson, 1984), a polymeroid trilobite distinctive for the Avalonian *Eccaparadoxides eteminicus* Zone (Geyer and Landing, 2001, p. 119; Kim and others, 2002). As *Tomagnostus fissus* also occurs at this locality, the age of Locality 1 is considered here to be no older than the upper half of the *Triplagnostus gibbus* Zone (Samson and others, 1990; Geyer and Landing, 2001). *T. fissus* is not known to occur below this level.

A case for a younger age can be made for Locality 5, as it yielded the diagnostic trilobite *Hypagnostus parvifrons*. This is the eponymous species for the *Hypagnostus parvifrons* biozone of Baltica. *Hypagnostus parvifrons* occurs upsection from the *Triplagnostus gibbus* biozone in Baltica and Britain (Rushton and Berg-Madsen, 2002).

Thus, three zones of the Middle Cambrian appear to be present at Batesburg—in descending order, the *Hypagnostus parvifrons* biozone (upper mid-Middle Cambrian; Locality 5), the *Tomagnostus fissus-Ptychagnostus atavus* global biozone (medial part of the mid-Middle Cambrian; represented by Locality 6) and the older *Eccaparadoxides eteminicus-Triplagnostus gibbus* global biozone (lowest zone of the

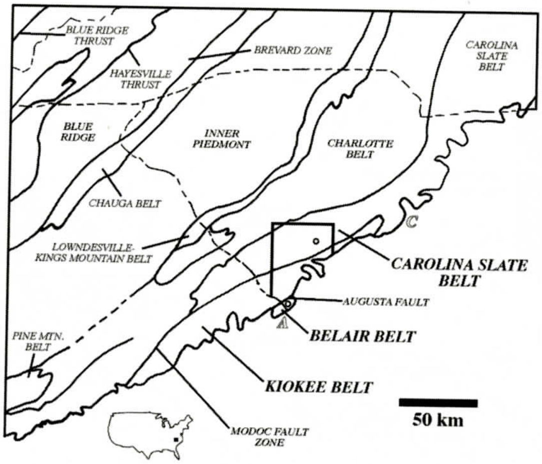


Figure 1. Generalized geologic map showing the position of the Belair Belt (Augusta terrane) and Carolina Slate Belt (Carolina terrane) in Georgia and South and North Carolina. Fossil localities for ptychoparioid genus and species A indicated with small circles (°). Inset map of United States shows approximate location of region. Partial box in the center of the figure shows approximate location of Figure 3. A indicates location of Augusta, Georgia; C indicates Columbia, South Carolina. Modified from Maher and others (1981).

mid-Middle Cambrian, represented by Locality 1, roughly equivalent to the *Badulesia tenera* Zone). These biozones are modified from a correlation chart by G. Geyer, S. C. Peng, and J. H. Shergold submitted to the International Subcommission on Cambrian Stratigraphy (Geyer and Landing, 2001, their Figure 2).

The Avalonian *Eccaparadoxides eteminicus* Zone correlates closely to the *Badulesia tenera* Zone of Morocco, a zone that has also been recognized in the Avalonian rocks of the Conanicut Group, Rhode Island (Skehan and others, 1978). Locality 1 may thus be precisely correlated to the *Badulesia tenera* Zone of the Conanicut Group of Jamestown, Rhode Island (Skehan and Rast, 1990). All of the Carolina trilobites appear to be older than the Rushton Brook Bed in Shropshire, Great Britain, recently assigned to the *Paradoxides forchhammeri* Zone (last zone of the Middle Cambrian; Rushton and Berg-Madsen, 2002). Note that Rushton and Berg-Madsen (2002) consider a *Hypagnostus parvifrons* subzone to constitute the upper half of their *Ptychagnostus atavus* Zone.

The Cambrian sequences of western Avalonia have paleobiogeographic similarities to Gondwanan terranes in Morocco (Geyer and Landing, 2001), Armorica and Bohemia (Samson, 1984; Samson and others, 1990). Avalonian occurrences of the stem-group brachiopod *Mickwitzia* (Landing and others, 1980; McMenamin 1992) and the trilobite *Nevadia burri* (McMenamin, 2001), however, suggest the presence at least limited shallow-water faunal interchange between Avalonia and North America during the Lower Cambrian.

REGIONAL CORRELATIONS

Most models of the genesis of the Carolina terrane follow the general Avalonian interpretation and portray the terrane as an island or volcanic arc (Nance and others, 2002; White and others, 2001). There is a continental crust component to the terrane as well, as the arc appears to have developed on basement of middle to late Proterozoic age (Mueller and others, 1996). Shervais and others (1996) suggest that the arc may have developed on a thinned sector of continental crust. Nance and others (2002) compare the separation of Avalonia from Gondwana in the Early Ordovician to the tectonic changes "brought about in Baja California by the Pliocene propagation of the East Pacific Rise

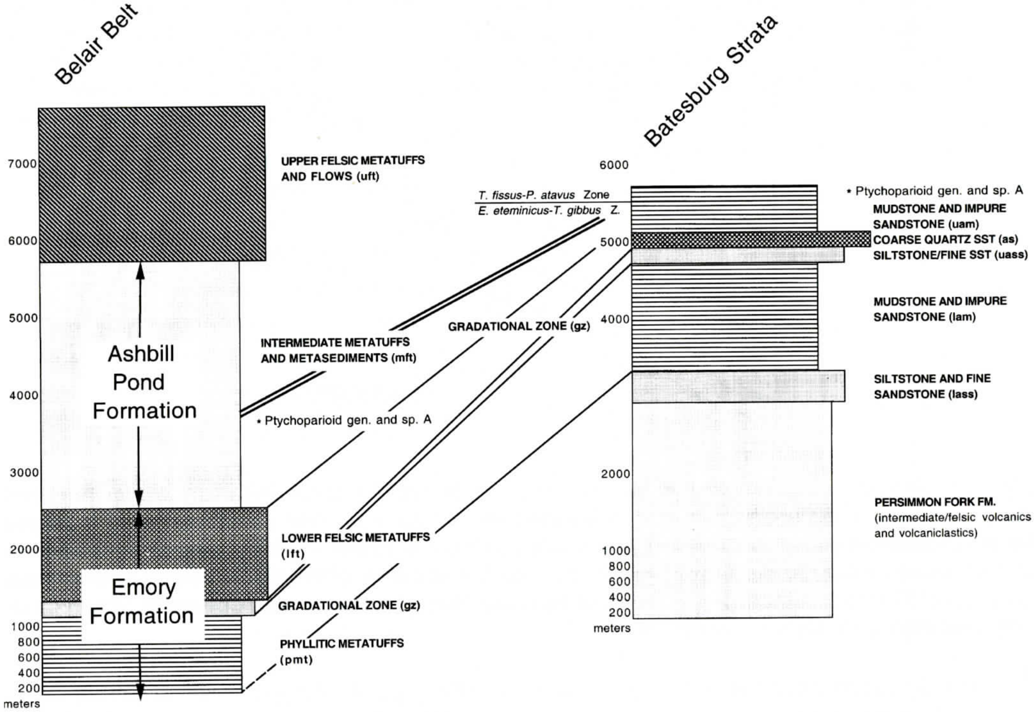


Figure 2. Biostratigraphic and lithostratigraphic correlation between Middle Cambrian and ?Lower Cambrian strata of the Belair Belt and the Batesburg region, Carolina Slate Belt. The Belair Belt section represents the northeastern part of the belt; the Carolina Slate Belt section represents the strata west of the Clouds Creek Igneous Complex (Samson and others, 1990). Double line indicates a line of biostratigraphic correlation; single line indicates lithostratigraphic correlation. Fossil occurrence indicated by (*). The thicknesses shown for individual beds are estimated.

into the continental margin" (p. 11).

The Carolina Slate Belt and the Belair Belt are separated across tens of kilometers by the migmatitic gneisses and synkinematic granites of the Kiokee Belt (Figure 1). A generalized correlation between the two belts has been proposed, and is based on similarities in their presumed tectonic setting (Maher and others, 1981). Coler and others (1996) found Sm-Nd isotopic support for this correlation. Belair Belt rhyolites yielded positive ε_{Nd} values of 6.1-6.5, comparable to those of the older portion of the Carolina terrane (ε_{Nd} = 0.5-5.8). Based on geochemical similarities between the Augusta terrane metavolcanics and the Richtex formation of the Carolina terrane, Shervais and others (1996) argued that the Augusta terrane represented a fragment of the Carolina terrane carried away in the hanging wall of the Augusta normal fault zone.

Biostratigraphic information provided by a newly characterized trilobite (ptychoparioid genus and species A; Maher and others, 1981; Samson, 1984) permits a fairly precise correlation at the lower to middle mid-Middle Cambrian level (*Tomagnostus fissus-Ptychagnostus atavus* biozone to *Eccaparadoxides eteminicus-Triplagnostus gibbus* biozone) between the rocks of the Belair Belt (Maher and others, 1981) and those of the Carolina Slate Belt (Figure 2).

The key fossil, ptychoparioid genus and species A, occurs in both the intermediate metatuffs and metasediments of the Belair Belt and in the upper mudstones and wackes of the Batesburg region (Figure 2). This biostratigraphic correlation implies a lithostratigraphic correlation as well between coarsening upward

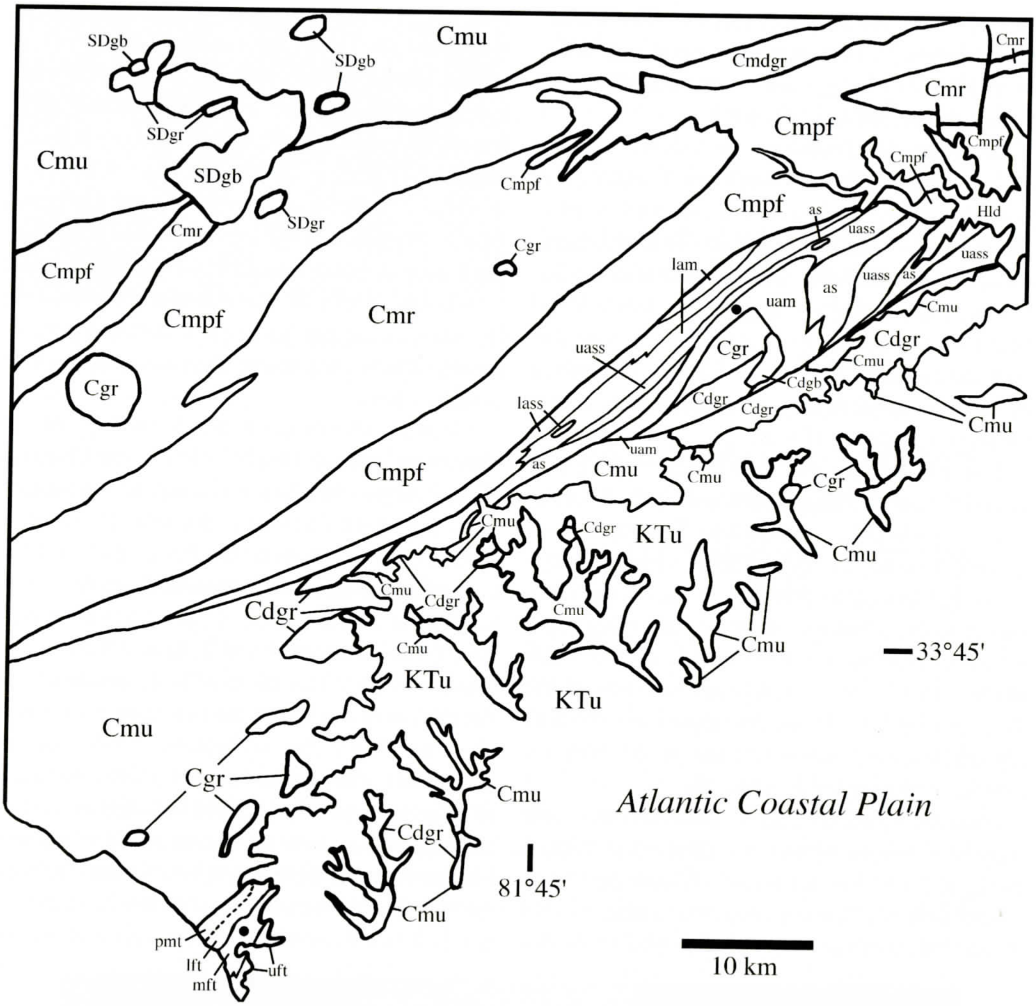


Figure 3. Geologic map of parts of the Belair Belt, Carolina Slate Belt and surrounding areas. Black circles (•) indicate fossil localities. Key: Cgr, Carboniferous undeformed granitic rock, Cdgr, Carb. deformed granitic rocks, Cdgb, Carb. deformed gabbroic rocks, SDgr, Siluro-Devonian undeformed granitic rocks, SDgb, Siluro-Devonian undeformed gabbroic rocks, Cmu, undifferentiated Cambrian metasediments and metavolcanics, Cmr, Richtex Formation, Cmpf, Persimmon Fork Formation, Cmdgr, Cambrian metaigneous rocks. For the Belair Belt: uft, upper felsic metatuffs and flows, mft, intermediate metatuffs and metasediments, Asbill Pond Formation, lft, lower felsic metatuffs, Emory Formation, gz, gradational zone, Emory Formation, pmt, phyllitic metatuffs, Emory Formation. For the Batesburg area; uam, upper mudstone and wacke, Asbill Pond Formation, as, coarse quartz sandstone, Emory Formation, uass, upper siltstone and fine sandstone, Emory Formation, lam, lower mudstone and wacke, Emory Formation, lass, siltstone and fine sandstone, Emory Formation. Geologic mapping data adapted from Maher and others (1981), Samson (1984) and Samson and others (1990), Secor and Snoke (2002) and unpublished field observations.

(and presumably shallowing upward) cycles of comparable thickness (roughly 1500+ and 1750 meters thick) in the Belair and Carolina Slate Belts, respectively. Thus the lower mudstones and wackes of Batesburg are taken here to correlate with the phyllitic metatuffs of the Augusta terrane, and the coarse quartz sandstone of Batesburg correlates to the lower felsic metatuffs of the Augusta terrane. The transitional intervals between the upper and lower parts of the cycle are also correlated between Belair and Batesburg (Figure 2).

All of the strata between the Asbill Pond Formation and the Persimmon Fork Formation at Batesburg are assigned (Secor and Snoke, 2002) to the Emory Formation. Thus the intermediate metatuffs and metasediments in the Belair Belt are assigned here to the Asbill Pond Formation, and the exposed strata below this unit are assigned here to the Emory Formation in accordance with the lithostratigraphic correlation to Batesburg (Figure 2).

Interestingly, Palmer (1981) placed the top of Grand Cycle H (Palmer's Grand Cycle 8) in the *Eccaparadoxides eteminicus-Triplagnostus gibbus* biozone. The correlation in Figure 2 suggests that this same grand cycle top may correspond to the lithologic contrast (implying rapid sea level rise) between the coarse quartz sandstone and the upper mudstone/wackes of the Batesburg Strata. If so, this represents the first recognition of North American grand cycle sequence stratigraphy in Avalonia.

This recognition of an Avalonian grand cycle may be extended further. Kim and others (2002) assigned the Fossil Brook Member of the Chamberlain's Brook Formation to both the *Eccaparadoxides eteminicus* Zone and to Avalonian depositional sequence 7 (Landing, 1996), and identified the unconformable top of the Fossil Brook Member as the upper sequence boundary for sequence 7. The base of the Fossil Brook Member was identified as the top of sequence 6 (Landing, 1996). We suggest here that this sequence boundary at the base of the Fossil Brook Member, a 30 cm thick basal pebbly sandstone at Saint John, New Brunswick (Kim and others, 2002), be correlated to Grand Cycle H or 8. A case can be made that these depositional hiatuses represent the same widespread eustatic event.

Figure 3 shows the bedrock geology of the eastern half of the Belair Belt and the Carolina Slate Belt geology in the vicinity of Batesburg. Note the similarities in strike and stratigraphy between the outcrops of the Belair Belt and the part of the Batesburg sequence immediately northwest of the Clouds Creek Igneous Complex (*Cgr* outcrops immediately south of the fossil locality). The strata of both terranes have similar strikes and have measured eastward dips of up to 86° (Maher and others, 1981; Samson and others, 1990). This supports the suggestion of Shervais and others (1996) of original lateral continuity between the strata in both regions. Further support for this hypothesis may be seen in the lithostratigraphic correlation lines in Figure 2. It is quite plausible (Shervais and others,

Figure 4. Plastotype of *Paradoxides harlani* Green 1834. Green's cast No. 39, Yale Peabody Museum (specimen 26760). The Yale label is heavy cardboard with glue mounting on the back suggesting that this cast was once on display. The arrow shows the position of a *Paradoxides* pygidial fragment mentioned in Green's (1834) text. Scale bar in centimeters.

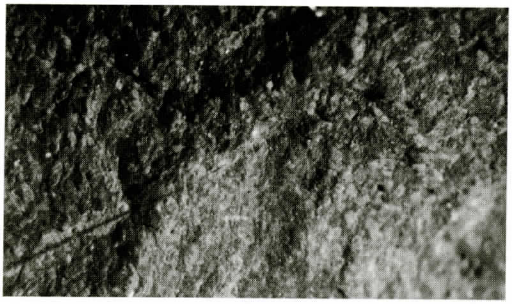


Figure 5. Pyrite vein in the Asbill Pond formation, USNM 443512. Width of view approximately 12 millimeters.

1996) that the observed separation between the terranes is due to displacement along the Augusta Fault Zone.

AVALONIA AND CRATONS

Paleobiogeographic base maps constructed for the Proterozoic-Cambrian boundary generally place Avalonia near Baltica, the Amazonian craton and the West African craton (Luetgert and Mann, 1990; van Staal and others, 1996; Nance and Murphy, 1996; Samson and Secor, 1999; Samson and others, 2001). Nance and Murphy (1996) proposed the presence of a laterally extensive subduction zone in this region. Its associated island arc and trench run in a remarkable stretch from the Carolina/Augusta terranes and the Suwannee terrane in Florida, to the rest of West Avalonia, to East Avalonia, to Cadomia in France, and finally to Spain.

Based on lithologic similarities, Dennis and Shervais (1996, their Figure 10, p. 343; perhaps taking a lead from Samson and others, 1990), argued for a closer linkage between the Carolina and Cadomian terranes than between the Carolina terrane and maritime New England or Canada. The fossil evidence presented here, however, more strongly supports the contention of Nance and Murphy (1996) that the Carolina, Augusta and the other West Avalonian terranes were juxtaposed. The subsequent fate of Avalonia is being assessed in the light of micropaleontological data (Samuelsson and Vecoli, 2001).

An interesting lithologic peculiarity shared by rocks of the Braintree Slate, Massachusetts (McMenamin, 2002) and the Asbill Pond formation is the occurrence of thin pyrite veins in the massive, fossiliferous dark gray (when fresh) siltstones. Figure 5 shows such a vein from the Asbill Pond formation.

SYSTEMATIC PALEONTOLOGY OF BATESBURG POLYMEROID TRILOBITES

Class Trilobita

Order Redlichiida

Superfamily Paradoxidoidea

Family Paradoxididae

Genus *Paradoxides* Brongniart, 1822

Discussion. The genus *Paradoxides* in the Americas came to international attention with Green's (1834) publication of a description of the species *Paradoxides harlani* from the Braintree Slate in eastern Massachusetts. Green (1834) did not provide an illustration of the holotype for the species, and this has led to discussion regarding the validity of the species. Geyer and Landing (2001, p. 128) noted that Green "proposed and described the species without an illustration, and his incomplete description does not permit an unambiguous identification." Jacob Green's specimens are thought to have been destroyed in a fire at the American Museum of Natural History in New York (James St. John, written communication, Dec. 10, 2003).

However, a cast residing in Yale University's Peabody Museum so closely matches Green's (1834) text description that it can be confidently identified as a plastotype (cast of the holotype) of *Paradoxides harlani*. Green's (1834) verbal description is detailed, accurate and fits this specimen precisely in terms of length ("nine inches") and preservation. For example, Green (1834, p. 337) notes that in "our specimen there is a small part of the tail of another trilobite deposited in this [posterior] place, which at first sight appears to be a dislocated fragment of our animal." This pygidial fragment is visible on the plastotype (arrow in Figure 4).

Tentative identifications of *Paradoxides* and *Conocryphe* were made in the Canadian Rockies (Mount Stephen and Kicking Horse Pass) in 1884, but these identifications subsequently proved to be incorrect (Gardiner, 2003).

Subgenus *Acadoparadoxides* Snajdr, 1957

Paradoxides (*Acadoparadoxides*) *grandoculus* n. sp.

(Figs 6-12)

Synonymy:

Paradoxides (or *Acadoparadoxides*). Secor and others, 1983.

Paradoxides davidis grandoculus [nomen nudum]. Samson, 1984.

Paradoxides cf. *polonicus*. Samson and others, 1990.

Paradoxides davidis grandoculus. Murphy, 1995.

Type specimen. USNM 443531.

Diagnosis. Well developed S1 and S2 on a pyriform glabella, S3 and S4 weak (small cranidia) to absent (large cranidia); long and relatively wide palpebral lobes. Anterolateral corners (corners occur approximately on the line of maximum glabellar width) of the subrectangular cranidium are angular and far forward. Posterior border of cranidium shows a distinct arch. Genal spine width varies from very narrow to moderate. Thorax bearing approximately 18-20 segments. Distal parts of pleurae are falcate; the length of the falcate portion increases progressively from the first to the penultimate segment (Samson and others, 1990, p. 1467). The last pleura robust and quite elongate. Pygidium subquadrate with a subtriangular axis. The lateral pygidial margins are subparallel with rounded posterior corners (Samson and others, 1990, p. 1467).

Remarks. This species of *Paradoxides (Acadoparadoxides)* has an exceptionally wide anterior glabella, although this may have been enhanced in some specimens by *post mortem* compression. The species also has very long eyes, as seen in specimen NCSM 7710-7711 (Figs. 10-11). *Paradoxides (Acadoparadoxides) grandoculus* n. sp. differs from other long-eyed paradoxidids such as *P. sacheri* and *P. mureroensis* "by having a medially narrower and more upturned anterior border on the cranidium and a subquadrate rather than a subhexagonal pygidium" (Samson and others, 1990, p. 1469). *P. (A.) grandoculus* n. sp. is distinguished from *P. (A.) harlani* (see especially Geyer and Landing [2001], their Figure 6) by having a considerably wider anterior glabellar lobe, comparable to *Paradoxides socius* from Poland (Orlowski, 1985). *P. socius* differs from *P. (A.) grandoculus* n. sp., however, by having a relatively straight posterior cranidial border furrow.

Paradoxides (Acadoparadoxides) grandoculus n. sp. may be distinguished from *Paradoxides polonicus* Orlowski by the fact that the posterior end of the eye in *P. polonicus* extends all the way back to the posterior cranidial border furrow (Orlowski, 1985, his Text-Figure 5a and his Plate 5, Figures 1, 2, and 4), whereas in *Paradoxides (Acadoparadoxides) grandoculus* n. sp. the posterior tip of each eye extends not as far, leaving a gap between the posterior of the eye and the border furrow. Furthermore, the field between the eye and glabella (i. e., the palpebral lobe plus the region of the fixigena posterior of the palpebral lobe but anterior of the border furrow) in *P. polonicus* is sublenticular and marked by a distinct abaxial furrow (i. e., the furrow opposite the glabellar furrow), whereas in *Paradoxides (Acadoparadoxides) grandoculus* n. sp. this field is subtriangular and has a much fainter distal or adaxial furrow, and is thus much more similar to the same field in *Paradoxides (Acadoparadoxides) harlani* than it is to the comparable field in *P. polonicus*. This suggests that, as appears to be the case in Lower Cambrian species of *Bristolia* that are distinguished on the basis of differences in their ESRs or eye spacing ratios (McMenamin and McMenamin, 2001b), the distinction noted here between *P. (A.) grandoculus* n. sp. and *P. polonicus* may be attributed to changes in homeotic gene expression (McMenamin and McMenamin, 2001b). *Paradoxides (Acadoparadoxides) grandoculus* n. sp. differs from *Para-*

Figure 6. *Paradoxides (Acadoparadoxides) grandoculus* n. sp., partial cephalon and thorax. USNM 443538, scale bar in centimeters.

Figure 8. *Paradoxides (Acadoparadoxides) grandoculus* n. sp., three cranidia, USNM 443530, USNM 443532, and an unnumbered cranidium (shown in Figure 9) with associated pleural fragment. Scale bar in centimeters.

Figure 7. *Paradoxides (Acadoparadoxides) grandoculus* n. sp., holotype, USNM 443531. A specimen of *Hypagnostus mammilatus* is visible at the upper right. Width of holotype 20.5 mm.

Figure 9. *Paradoxides (Acadoparadoxides) grandoculus* n. sp., cranidium. See Figure 8 caption for repository information. Scale bar in millimeters.

Figure 10. *Paradoxides (Acadoparadoxides) grandoculus* n. sp., right librigena, counterpart. Note the large size of the ocular lobe margin. NCSM 7711; field sample 1 of 6/28/02. Specimen length 34 mm.

Figure 11. *Paradoxides (Acadoparadoxides) grandoculus* n. sp., right librigena, part. NCSM 7710; field sample 2 of 6/28/02. Specimen length 34 mm.

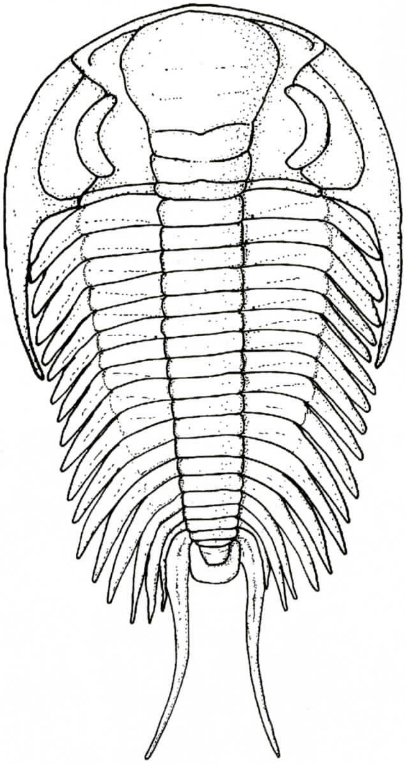


Figure 12. *Paradoxides (Acadoparadoxides) grandoculus* n. sp., reconstruction of entire dorsal carapace. Maximum length of trilobite approximately 7-8 cm.

doxides davidis by having a more nearly straight, rather than chevron-shaped, posterior cephalic margin.

A case could be made that a terminologically valid subspecies *Paradoxides (Acadoparadoxides) grandoculus grandoculus* now exits, as Murphy (1995, p. 174) published Samson's (1984) nomen nudum *Paradoxides davidis grandoculus* along with five illustrations of the trilobite taken from Samson and others (1990). It was not Murphy's (1995) intent to describe a new subspecies, however, and as no description

Figure 13. *Eccaparadoxides eteminicus* (Matthew, 1883). Cranidium, USNM 443529. Width of specimen from outer edges of the left and right ocular lobes 13.5 mm.

was attempted, the subspecies is considered here to be terminologically invalid.

Distribution and age. Asbill Pond Formation of South Carolina, Carolina Terrane, Middle Cambrian, localities 1, 2, 3, and 6 of Samson and others (1990). *Tomagnostus fissus-Ptychagnostus atavus* global biozone (medial part of the mid-Middle Cambrian) to *Eccaparadoxides eteminicus-Triplagnostus gibbus* global biozone (lowest zone of the mid-Middle Cambrian).

Genus *Eccaparadoxides* Snajdr, 1957

Eccaparadoxides eteminicus (Matthew, 1883)

(Fig 13)

Synonymy:

Paradoxides cf. *P. eteminicus.* Samson, 1984.

Paradoxides sp. Samson and others (1990).

[For complete synonymy, see Kim and others (2002).]

Diagnosis. A species of *Eccaparadoxides* with a distinctive "Edison light-bulb" shaped glabella and a long pygidial axis (Kim and others, 2002). The species also may develop a club-shaped swelling or inflection at the posterior end of the ocular lobe.

Remarks. Samson and others (1990, their Figure 6H) left this species in open nomenclature due to insufficient knowledge of its exoskeleton. The South Carolina specimens, however, bear such great similarity (particularly in the shape of the glabella, the number of glabellar furrows, the width of the ocular lobes, and the posterior border of the librigena) to recently illustrated specimens (Kim and others, 2002) of *E. eteminicus* that the South Carolina specimens can confidently be assigned to this species.

Distribution and age. In South Carolina, Asbill Pond Formation, Middle Cambrian, locality 1 of Samson and others (1990). *Eccaparadoxides eteminicus-Triplagnostus gibbus* global biozone (lowest zone of the mid-Middle Cambrian).

Order Ptychopariida

Suborder Ptychopariina

Superfamily Solenopleuroidea

Family Conocoryphidae

?*Conocoryphe* sp.

Figs. 14-15

Description. A conocoryphid trilobite with a long (sag.) preglabellar field. A prominent palpebral ridge is present on internal molds of the cranidium.

Remarks. The single South Carolina specimen of this species (Figs. 14-15) is a cranidium in-

Figure 14. *?Conycoryphe* sp., cranidium interior, one of two cranidia on the same piece of rock. NCSM 7712; field sample 1 of 7/2/02. Scale bar in mm.

Figure 15. *?Conycoryphe* sp., polysiloxane mold (forming an artificial cast) of the cranidium in Figure 4. Scale bar in mm.

ternal mold with a wide preglabellar field and palpebral lobes (very faintly visible on this specimen).

This is the first conocoryphid trilobite to be reported from the Batesburg fauna. The specimen may belong to either of the genera *Conocoryphe* or *Bailiella*, but more complete material is required before making a confident generic assignment.

Distribution and age. Asbill Pond Formation, Middle Cambrian, locality 1 of Samson and others (1990). *Eccaparadoxides eteminicus-Triplagnostus gibbus* global biozone (lowest zone of the mid-Middle Cambrian).

Family ?Agraulidae

Genus *Skehanos* McMenamin, 2002

Skehanos sp.

Synonymy:

Solenopleura? sp. #1. Samson, 1984.

Agraulidae [species 2]. Secor and others, 1983.

Skehanos quadrangularis (Whitfield, 1884). McMenamin, 2002.

Remarks. The single South Carolina specimen of this genus (Samson and others, 1983, their Figure 2g) has 11 thoracic segments exposed and is roughly 8 mm long by 4 mm wide (Samson, 1984). As noted by Samson (1984, p. 42), the cranidium of this species has an approximate length to width 1:1.5, a highly convex glabella, and a broad preglabellar field that arches down laterally.

Description. A ptychoparioid trilobite bearing an effaced cephalon and glabella but a distinct axial furrow; glabella swollen and bullet-shaped; glabellar furrows faint to obsolete; straight pleural furrows that deepen distally; and a pygidium consisting of a posteriorward extension of the axial lobe beyond the posteriormost pleural tergite.

Although assigned by McMenamin (2002) to the species *Skehanos quadrangularis*, we consider this specimen not well enough preserved to permit a species assignment. The specimen does nevertheless match the description for the genus *Skehanos*.

The systematic relationship of the genus *Skehanos* to Middle Cambrian trilobites referred by Orlowski (1985; his Plate 1) to *Ellipsocephalus sandomiri* is not known (the cranidia of the trilobites are quite different). We consider the similarities in the degree of glabellar effacement and the similarities with regard to the posterior cranidial margin of these two types of trilobites to be due to homeomorphy.

Distribution and age. In South Carolina, Asbill Pond formation, Middle Cambrian, locality 1 of Samson and others (1990). *Eccaparadoxides eteminicus-Triplagnostus gibbus* global biozone (lowest zone of the mid-Middle Cambrian). The genus *Skehanos* apparently ranges through three biozones (Geyer and Landing, 2001) of the Middle Cambrian, as the earliest occurrences are known from the lower Middle Cambrian *Paradoxides (Acadoparadoxides) harlani* Zone (McMenamin, 2002).

Family uncertain

Genus *Braintreella* Wheeler, 1942

Braintreella sp.

(Fig 16)

Synonymy:

Parasolenopleura sp. Samson, 1984.

?Agraulos sp. Samson and others, 1990 [their Figure 6f].

Braintreella sp. McMenamin and Weaver,

Figure 16. *Braintreella* sp. cranidium from the Asbill Pond formation. USNM 443527. Width of specimen 13.7 mm.

2002.

Description. A solenopleurid trilobite with tapering, smooth-surfaced, subtruncate glabella and distinctive preglabellar field and anterior border. The anterior border consists in part of a straight or nearly straight line or depression perpendicular to (and centered on) the long axis of the glabella.The straight section is terminated on both sides by an inflection point, followed by curving of the anterior border toward the posterior of the animal. The length of the straight section of the anterior border approximately equals the length (sag.) of the glabella.

Remarks. Although *Braintreella* is rather nondescript trilobite, its anterior cranidial border is distinctive enough to distinguish it from other ptychoparioid genera with a smooth glabella and an occipital spine such as *Marjuma* and *Modocia*. The Batesburg specimens have strong similarities to specimens from Massachusetts and thus should be assigned to *Braintreella*.

This trilobite differs at the species level from *Braintreella rogersi* (Walcott, 1884) in the length of the straight section of its anterior border. In *Braintreella* sp., the length of the straight section of the anterior border approximately equals the length (sag.) of the glabella, whereas in *Braintreella rogersi*, the length of the straight section of the anterior border usually exceeds the length (sag.) of the glabella. See, however, the specimen of *B. rogersi* illustrated by Harrington and others [1959, their Figure 170.1], where the straight section of the anterior border is subequal to the length of the glabella. Also, the anterior border of *Braintreella* sp. is higher relief (especially its anteriormost edge) than is the case in *B. rogersi*.

Braintreella sp. is now known from two cranidia (Samson and others, 1990, their Figure 6f), one of which consists of inner and outer test of a single cranidium (Samson, 1984, her Plate 6, Figures H-J).

Considering its similarity to *B. rogersi* Wheeler, 1942 (particularly in terms of the presence of a short occipital spine), the trilobite referred to by Samson and others (1990, their Figure 6G) as *?Skreiaspis* sp. and as *?Agraulos* sp. by Samson (1984, her Plate 6, Figures F-G) might best be included in the genus *Braintreella* as well. Note especially its strong similarity to the specimen of *B. rogersi* illustrated by Harrington and others [1959, their Figure 170.1]. *?Skreiaspis* sp. could conceivably be an ecophenotypic variant or sexual dimorph of *Braintreella* sp., especially seeing as the forms co-occur in the intervals 100-80 feet and 45-60 feet at Samson's (1984) locality 1.

Distribution and age. Asbill Pond formation, Middle Cambrian, locality 1 of Samson and others (1990). *Eccaparadoxides eteminicus-Triplagnostus gibbus* global biozone (lowest zone of the mid-Middle Cambrian).

Ptychoparioid genus and species A

(Fig. 17)

Synonymy:

?Pliomeridae. Maher and others, 1981.
Solenopleura? sp. #2. Samson, 1984.
Skehanos-like trilobite thorax. McMenamin, 2002.

Diagnosis. A ptychoparioid trilobite with a wide cranidium, largely effaced glabella, and preglabellar area that gives way to an unusually wide, upturned anterior cranidial border. Palpebral lobes indistinct. Unusually wide pleural re-

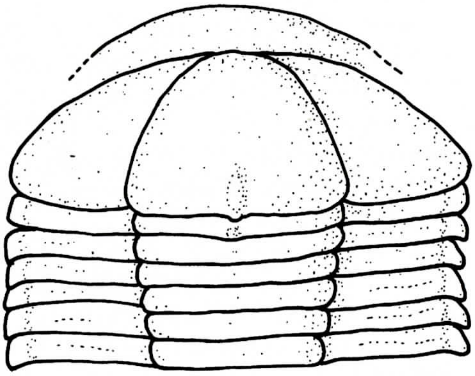


Figure 17. Ptychoparioid genus and species A sketch after Samson (1984, her Plate 6, Figure O). Posterior thoracic region and pygidium unknown. Maximum width of trilobite approximately 20 mm.

gions, with relatively uniform thoracic segments. Pygidium unknown.

Remarks. Ptychoparioid genus and species A is an olenimorph trilobite characterized by its wide cephalon and uniform thoracic segments. The wide thorax described by Maher and others (1981) is considered here to be conspecific with the unusually wide form (Figure 17) described by Samson (1984). Family, genus and species assignment of this trilobite must await recovery of more complete material.

The trilobite may be distinguished from *Skehanos* by the greater relative width of its axial lobe and cephalon, by the shape of its glabella, and by its upturned anterior cranidial border. Ptychoparioid genus and species A differs from members of the Ordovician family Pliomeridae by having a glabella with indistinct glabellar furrows. The glabellar furrows in pliomerid trilobites are deeply incised.

A Middle Cambrian age can be provided for the felsic and phyllitic metatuffs of the Belair Belt of Georgia and South Carolina, based on the presence of ptychoparioid genus and species A. Furthermore, correlation may now be made at the lower-mid mid-Middle Cambrian level between the compositionally intermediate metatuffs and metasedimentary rocks of the Belair Belt (map unit *mts* of Maher and others, 1981) and locality 2 of the Batesburg region (Figure 2).

Distribution and age. Asbill Pond formation of South Carolina, Carolina Terrane, Middle Cambrian, locality 2 of Samson and others (1990). *Tomagnostus fissus-Ptychagnostus atavus* biozone (medial part of the mid-Middle Cambrian) or *Eccaparadoxides eteminicus-Triplagnostus gibbus* biozone (lowest zone of the mid-Middle Cambrian); metatuffs and metasedimentary rocks of the Belair Belt (map unit *mts* of Maher and others, 1981), Belair Belt, South Carolina and Georgia.

ACKNOWLEDGEMENTS

Thanks to Michelle Markley for discussion of the geological structure of Avalonia, to D. T. Secor, C. Ciampaglio and R. A. Robison for reviews, to D. T. Secor and A. W. Snoke for providing map data, to Mark Florence and Dan Levin for assistance with specimen loans, and to Dianna McMenamin, Amy McMenamin and Jessica McMenamin for field assistance. NCSM numbers refer to specimens in the North Carolina State Museum of Natural Sciences; USNM numbers to the United States National Museum.

REFERENCES CITED

Barr, S. M., White, C. E., Miller, B. V., and van Staal, C. R., 2002, The myth of "Avalonia": Did it constitute a single terrane or several different terranes in the Early Paleozoic?: Geological Society of America abstracts, v. 34, p. 28.

Briggs, D. E. G. and Robison, R. A., 1984, Exceptionally preserved nontrilobite arthropods and *Anomalocaris* from the Middle Cambrian of Utah: The University of Kansas Paleontological Contributions, v. 111, p. 1-23.

Brongniart, A., 1822, Histoire naturelle des Crustacés fossiles sous les rapports zoologique et géologique, savoir le Trilobites. Les Crustacés proprement dits par A.-G. Desmarest: Paris, F. G. Levrault, 154 p.

Clapham, M. E. and Narbonne, G. M., 2002, Ediacaran epifaunal tiering: Geology, v. 30, p. 627-630.

Coler, D. G., Samson, S. D. and Stoddard, S., 1996, Terrane correlation and characterization in the Southern Appalachians; an Sm-Nd isotopic investigation: Eos, Supplement, v. 77, n. 17, p. 290.

Dawson, J. W., 1868, Acadian Geology: The Geological Structure, Organic Remains and Mineral Resources of Nova Scotia, New Brunswick, and Prince Edward Island: London, Macmillan, 694 p.

Dennis, A. J. and Shervais, J. W., 1996, The Carolina terrane in northwestern South Carolina: Insights into the development of an evolving island arc *in* R. D. Nance and M. D. Thompson, eds., Avalonian and related peri-Gondwanan Terranes of the Circum-North Atlantic: Boulder, Colorado, Geological Society of America Special Paper 304, v. p. 237-256.

Gardiner, B., 2003, Editorial: The Linnean, v. 19, n. 1, p. 1-3.

Geyer, G. and Landing, E., 2001, Middle Cambrian of Avalonian Massachusetts: Stratigraphy and correlation of the Braintree trilobites: Journal of Paleontology, v. 75, p. 116-135.

Green, J., 1834, Descriptions of some new North American trilobites: American Journal of Science, v. 25, p. 334-337.

Harrington, H. J. and others, 1959, Systematic Descriptions *in* R. C. Moore, ed., Treatise on Invertebrate Paleontology, Part O, Arthropoda 1. Geological Society of America and University of Kansas Press, Lawrence, Kansas, v. p. O170-O560.

Hatcher, R. D., 2000, Facts that delimit Southern Appalachian plate models and tectonic implications: Geological Society of America Abstracts with Programs, v. 32, p. 25.

Kim, D. H., Westrop, S. R. and Landing, E., 2002, Middle Cambrian (Acadian Series) conocoryphid and paradoxidid trilobites from the Upper Chamberlain's Brook Formation, Newfoundland and New Brunswick: Journal of Paleontology, v. 76, p. 822-842.

Landing, E., 1996, Avalon: insular continent by the latest Precambrian *in* R. D. Nance and M. D. Thompson, eds., Avalonian and related peri-Gondwanan terranes of the circum-North Atlantic: Boulder, Colorado, Geological Society of America Special Paper 304, v. p. 29-63.

Landing, E., Nowlan, G. S. and Fletcher, T. P. 1980. A microfauna associated with Early Cambrian trilobites of the *Callavia* Zone, northern Antigonish Highlands, Nova Scotia: Canadian Journal of Earth Science, v. 17, p. 400-418.

Luetgert, J. and Mann, C. E. 1990. Avalon terrane in eastern coastal Maine: Seismic refraction-wide-angle reflection data: Geology, v. 18, p. 878-881.

Maher, H. D., Palmer, A. R., Secor, D. T. and Snoke, A. E., 1981, New trilobite locality in the Piedmont of South Carolina and its regional implications: Geology, v. 9, p. 34-36.

Matthew, G. F., 1883 [1882], Illustrations of the fauna of the St. John Group, No. 1. The *Paradoxides*: Transactions of the Royal Society of Canada, v. 2, p. 271-279.

McMenamin, M. A. S., 2002, The ptychoparioid trilobite *Skehanos* gen. nov. from the Middle Cambrian of Avalonian Massachusetts and the Carolina Slate Belt, USA: Northeastern Geology and Environmental Science, v. 24, p. 276-281.

McMenamin, M. A. S., 2001a, Part V. A new nevadiid trilobite recognized from Sonora, Mexico *in* M. A. S. McMenamin, ed., Paleontology Sonora: Lipalian and Cambrian: South Hadley, Massachusetts, Meanma Press, v. p. 103-106.

McMenamin, M. A. S. and McMenamin, S. K., 2001b, Part VI. Homeotic genes, the antennapedia complex in the trilobite genome, and iterative evolution in nevadiid and bristoliid trilobites *in* M. A. S. McMenamin, ed., Paleontology Sonora: Lipalian and Cambrian: South Hadley, Massachusetts, Meanma Press, v. p. 107-113.

McMenamin, M. A. S., 1992, Two new species of the Cambrian genus *Mickwitzia*: Journal of Paleontology, v. 66, p. 173-182.

McMenamin, M. A. S. and Weaver, P. G., 2002, Proterozoic-Cambrian paleobiogeography of the Carolina Terrane: Southeastern Geology, v. 41, p. 119-128.

Mueller, P. A., Kozuch, M., Heatherington, A. L., Wooden, J. L., Offield, T. W., Koeppen, R. P., Klein, T. L. and Nutman, A. P., 1996, Evidence for Mesoproterozoic basement in the Carolina terrane and speculations on its origin *in* R. D. Nance and M. D. Thompson, eds., Avalonian and related peri-Gondwanan Terranes of the Circum-North Atlantic: Boulder, Colorado, Geological Society of America Special Paper 304, v. p. 207-217.

Murphy, C. H., 1995, Carolina Rocks! The Geology of South Carolina: Orangeburg, South Carolina, Sandlapper Publishing Company, 261 p.

Murphy, J. B., 2002, Geochemistry of the Neoproterozoic metasedimentary Gamble Brook Formation, Avalon Terrane, Nova Scotia; evidence for a rifted-arc environment along the West Gondwanan margin of Rodinia: Journal of Geology, v. 110, p. 407-419.

Nance, R. D. and Murphy, J. B., 1996, Basement isotopic signatures and Neoproterozoic paleogeography of Avalonian-Cadomian and related terranes in the circum-North Atlantic *in* R. D. Nance and M. D. Thompson, eds., Avalonian and related peri-Gondwanan Terranes of the Circum-North Atlantic: Boulder, Colorado, Geological Society of America Special Paper 304, v. p. 333-346.

Nance, R. D, Murphy, J. B. and Keppie, J. D., 2002, A Cordilleran model for the evolution of Avalonia: Tectonophysics, v. 352, p. 11-31.

Orlowski, S., 1985, New data on the Middle Cambrian trilobites and stratigraphy in the Holy Cross Mountains: Acta Geologica Polonica, v. 35, p.251-263.

Palmer, A. R., 1981, On the correlatability of Grand Cycle tops *in* M. E. Taylor, ed., Short Papers for the Second International Symposium on the Cambrian System: United States Geological Survey Open-File Report 81-743, v. p. 156-159.

Peterson, K. J., Waggoner, B. and Hagadorn, J. W., 2003, A fungal analog for Newfoundland Ediacaran fossils: Integrative and Comparative Biology, v. 43, p. 127-136.

Robison, R. A., 1982, Some Middle Cambrian agnostid trilobites from Western North America: Journal of Paleontology, v. 56, p. 132-160.

Rushton, A. W. A. and Berg-Madsen, V., 2002, The age of the Middle Cambrian '*Paradoxides forchhammeri* Grit' of the Wrekin district, Shropshire, England: Transactions of the Royal Society of Edinburgh, v. 92, p. 335-346.

Samson, S. D. and Secor, D. T., 1999, Cambrian paleogeography of the Carolina terrane: constraints from U-Pb ages of detrital zircons: Geological Society of America Abstracts with Programs, v. 33, p. A-71.

Samson, S. D., Secor, D. T. and Hamilton, M. A., 2001, Wandering Carolina: Tracking exotic terranes with detrital zircons: Geological Society of America Abstracts with Programs, v. 33, p. A-263.

Samson, S. L., 1984, Middle Cambrian Fauna of the Carolina Slate Belt, Central South Carolina. Master's Thesis, University of South Carolina.

Samson, S., Palmer, A. R., Robison, R. A. and Secor, D. T., 1990, Biogeographical significance of Cambrian trilobites from the Carolina Terrane: Geological Society of America Bulletin, v. 102, p. 1459-1470.

Samuelsson, J. and Vecoli, M., 2001, Tracing the fate of Avalonia; micropaleontological answers to a geological conundrum: PaleoBios, v. 21 (2 Suppl. 2), p. 112.

Secor, D. T., Samson, S. L., Snoke, A. W. and Palmer, A. R., 1983, Confirmation of the Carolina Terrane as an exotic terrane: Science, v. 221, p. 649-651.

Secor, D. T. and Snoke, A. W., 2002, Explanatory notes to accompany the geologic map of the Batesburg and Emory quadrangles, Lexington and Saluda Counties, South Carolina: Geological Society of America Map and Chart Series MCH091, p. 1-32.

Shervais, J. W., Shelley, S. A. and Secor, D. T., 1996, Geochemistry of volcanic rocks of the Carolina and Augusta terranes in central South Carolina: An exotic rifted volcanic arc? *in* R. D. Nance and M. D. Thompson, eds., Avalonian and related peri-Gondwanan Terranes of the Circum-North Atlantic: Boulder, Colorado, Geological Society of America Special Paper 304, v. p. 219-236.

Skehan, J. W. and Rast, N., 1990, Pre-Mesozoic evolution of Avalon terranes of southern New England: Boulder, Colorado, Geological Society of America Special Paper 245, v. p. 13-53.

Skehan, J. W., Murray, D. P., Palmer, A. R., Smith, A. T. and Belt, E. S., 1978, Significance of fossiliferous Middle Cambrian rocks of Rhode Island to the Avalonian microcontinent: Geology, v. 6, p. 694-698.

Snajdr, M., 1957, Trilobiti aeskeho stredniho kambria: Vestnik Ustredního ústavu Geologicky, v. 32, p. 235-244.

van Staal, C. R., Sullivan, R. W. and Whalen, J. B., 1996, Provenance and tectonic history of the Gander Zone in the Caledonian/Appalachian orogen: Implications for the origin and assembly of Avalon *in* R. D. Nance and M. D. Thompson, eds., Avalonian and related peri-Gondwanan Terranes of the Circum-North Atlantic: Boulder, Colorado, Geological Society of America Special Paper 304, v. p. 671-724.

White, C. E., Barr, S. M., Jamieson, R. A. and Reynolds, P. H., 2001, Neoproterozoic high-pressure/low-temperature metamorphic rocks in the Avalon terrane, southern New Brunswick, Canada: Journal of Metamorphic Geology, v. 19, p. 517-528.

Williams, H. and Hatcher, R. D., 1982, Suspect terranes and accretionary history of the Appalachian orogen: Geology, v. 10, p. 530-536.

Wilson, J. T., 1966, Did the Atlantic close and then re-open?: Nature, v. 211, p. 676-681.

SOUTHEASTERN GEOLOGY
V. 43, No. 1, August 2004, p. 39-50

THE ORIGIN, DEVELOPMENT, AND EVENTUAL CONSOLIDATION OF THE CANYONS COMPRISING PROVIDENCE CANYON STATE PARK, STEWART COUNTY, GEORGIA

CARL R. FROEDE JR.

United States Environmental Protection Agency
Region 4
61 Forsyth Street
Atlanta, GA 30303-8960

EMMETT L. WILLIAMS

Lockheed Martin Corporation (Ret.)
P.O. Box 2006
Alpharetta, GA 30023

ABSTRACT

Nine canyons of varying sizes occur in Providence Canyon State Park in Stewart County, Georgia. These features likely originated in the early 1800s as a result of poor farming practices. Overland flow across cleared fields initiated rills that developed into gullies. The erosion of the overlying sandy-clay Clayton Formation exposed the poorly consolidated and easily weathered sands and clays of the Providence Sand and upper Ripley formations. Accelerated headward erosion occurred in the clastic sedimentary units especially where gullying intercepted the groundwater table. As a result, steep-sided, narrow and deep canyons were rapidly formed. Today, the canyons found in the park have eroded headward nearly to the top of the topographic divide. Overland flow is no longer the dominant erosional process shaping the canyons. Cliff-and spring-sapping conditions now have control over canyon development by removing sidewall-eroded clastic sediments and widening the canyon floors. What were once V-shaped canyons formed and maintained by overland flow are now maturing into ever widening U-shaped canyons dominated by groundwater sapping processes. Under these hydrogeologic conditions, the canyon sidewalls that lie within the zone of saturation are undermined by sapping and are removed by spring-fed flow on the canyon floors. If this groundwater-driven erosional activity continues then the individual canyons will eventually consolidate into one large amphitheater basin.

INTRODUCTION

Providence Canyon State Park is located in Stewart County, in southwestern Georgia (Figure 1). The Park consists of nine canyons that range from 31 to 50 m in depth, and from 180 to 405 m in length (Figure 2). The canyons formed as a direct result of poor-farming techniques. Two different erosional processes have shaped the canyons: (i) overland flow, and (ii) cliff- and spring-sapping. Rills rapidly formed once uncontrolled overland flow was initiated. Gullying developed shortly thereafter. Eventually, canyons incised sufficiently to intercept the groundwater table. Today, the groundwater processes of cliff- and spring-sapping dominate the development of the many canyons.

PROVIDENCE CANYON STATE PARK

The park, known throughout the southeastern United States as "Georgia's Little Grand

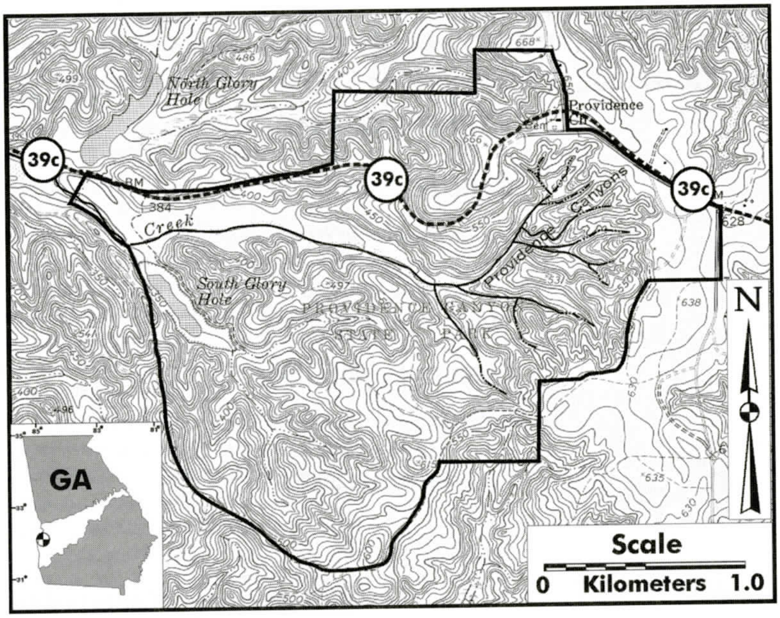


Figure 1. Providence Canyon State Park, Stewart County, Georgia. Inset map shows the Fall Line Hills and the location of the Park in that province. While overland flow initiated the formation of the canyons, groundwater sapping now dominates canyon development. From U.S. Geological Survey 7.5 Minute Quadrangle, Lumpkin SW, GA., 1955–revised 1993. Contour interval is 10 feet.

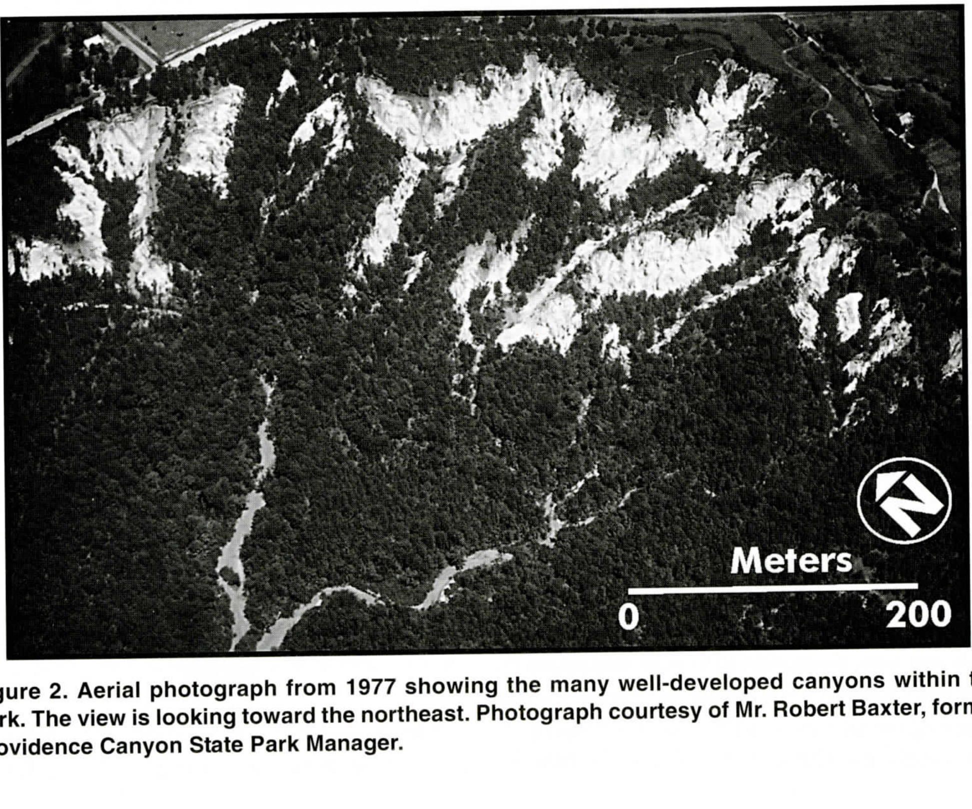


Figure 2. Aerial photograph from 1977 showing the many well-developed canyons within the Park. The view is looking toward the northeast. Photograph courtesy of Mr. Robert Baxter, former Providence Canyon State Park Manager.

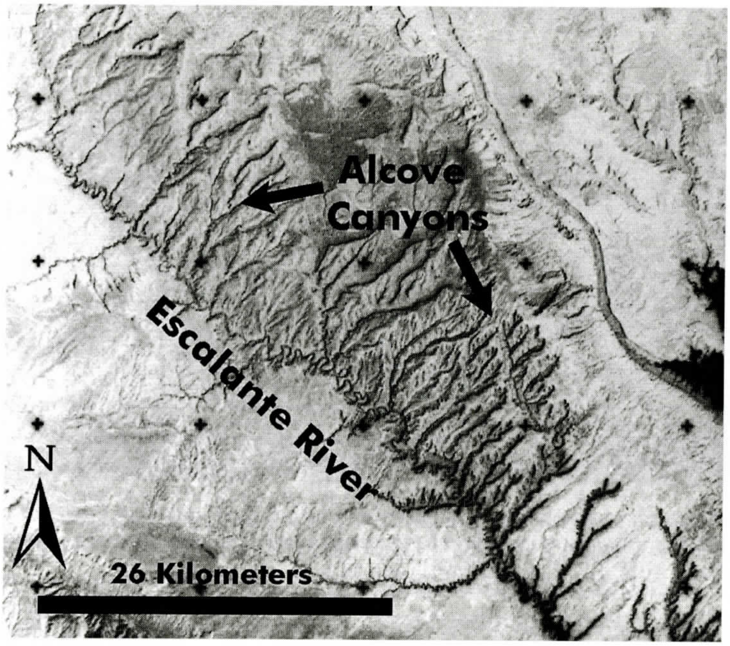


Figure 3. A portion of the Escalante River on the Colorado Plateau. Prehistoric groundwater sapping at the base of the Navajo Sandstone/top of the Kayenta Formation, on the northeastern side of the river, has created multiple alcove-headed canyons. The processes that created these canyons in the past occur today at Providence Canyon State Park, Georgia. Image credit: Landsat 30914-17091-A, September 4, 1980, NASA/JPL.

Canyon," was officially established in 1971, for the protection and preservation of the local flora and fauna (Anonymous, 1981; Beach and Magilligan, 1993). Named for a church adjacent to the many canyons, Providence Canyon State Park covers 449 ha of which approximately one-third is impacted by the many canyons. It contains rather unique plant life for this latitude because of the warm micro-climate created by the multiple high canyon sidewalls and adjoining alcoves. Excellent facilities and extensive walking trails make exploration and investigation of the Park an enjoyable experience.

The many gullies and canyons found in the Park have been attributed to anthropogenic influences (Sisk, 1935; Donovan and Reinhardt, 1980; Anonymous, 1981; Joyce, 1985), based on the many similarities with other gully/canyon systems (e.g., Ireland, 1939; Ireland and others, 1939; Twidale, 1968; Trimble, 1974; Wells and Andriamihaja, 1993). However, geologic analysis of images collected from satellites orbiting the Earth since the 1970s has broadened our understanding of canyon formation to include other important erosional processes. As a result, the many canyons in Providence Canyon State Park provide an interesting small-scale analog to large-scale groundwater sapping features prehistorically developed on the Colorado Plateau (Laity and Malin, 1985; Graf and others, 1987; Howard and others, 1988) [Figure 3].

GEOMORPHOLOGY

Providence Canyon State Park is in the red-capped hills portion of the Fall Line Hills Province (Veatch and Stephenson, 1911). According to Cooke (1943), the Fall Line Hills correspond to a belt of largely Upper Cretaceous clastic sediments that extend across the state immediately south of the Piedmont. Clark and Zisa (1976) define the Fall Line Hills District as highly dissected with little level land, and stream valleys 50 to 250 feet below the adjacent ridge tops.

Figure 4. A photograph of one of the well-developed V-shaped canyons from Vetch (1909). There appears to be little significant vegetation in the background on the right side of the image. Today the area is covered primarily in a southern pine forest.

Gully erosion has been studied in this province since Sir Charles Lyell first observed these geomorphic features on his visit to Georgia in 1846 (Ireland, 1939). By the turn of the twentieth century, the area around the Providence Methodist Church was well known for its distinctive deep gullies (Figure 4). The original church (circa 1830s) was later rebuilt in 1859 at a higher elevation because of the developing canyons (Georgia Historical Commission, no date). Veatch and Stephenson (1911, p. 29-30) describe the geomorphic setting of this particular area as:

> The deep gullies, also known as "washes" and "caves," which appear in this region, are worthy of note. The softness of the strata together with the high altitudes of the plain above the rivers, timber denudation, and cultivation of the land, have been especially favorable for rapid erosion, and some of the deepest gullies, 100 to 175 feet, are known to have formed since the settlement of the country.
>
> The gullies at Providence, eight miles west of Lumpkin, are 100 to 175 feet in depth, and from 200 yards to one-fourth mile in length. The recession of the gullies has been very rapid, and the deepest gully is known to have worked back 300 feet in about 30 years, and to have washed out a space of 10 to 15 acres.

Several legends describe how the canyons are thought to have originated (see Appendix I). We believe the canyons formed as a result of poor farming practices (see Donovan and Reinhardt, 1980; Joyce, 1985) combined with an initially shallow groundwater table. Paleolimnologists Hyatt and Gilbert (2000), using ^{210}Pb chronology on sediments from two small lakes downstream from the canyons, suggest that the time of greatest erosion probably began in the 1840s and that by 1880 the level of erosion had decreased to near present-day conditions. Geomorphologists Magilligan and Stamp (1997) documented a similar history for the canyons found in the Park using trench excavation, aerial photography, and computerized storm models.

The topography of the area is dominated by a southern progression of westwardly flowing dendritic steams separated by cuesta ridges adjoined in places to plateau-like uplands, all of which is likely controlled by underlying basement features. Regional uplift of the area during the Mesozoic and early Cenozoic (Stephenson, 1928; Cooke, 1943; Reinhardt and others, 1984;

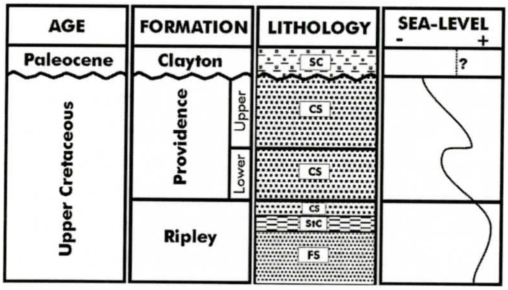


Figure 5. Providence Canyon stratigraphic column with sea-level curve. Adapted from Donovan and Reinhardt (1986, Figure 4, p. 361) and Reinhardt and Gibson (1980, Figure 6, p. 392). The lithologic units are defined as follows: SC - sandy clay, CS - course-grained sand, FS - fine-grained sand, StC - silty clay. The Clayton Formation contains confusing sedimentary evidence for both a carbonate and fluvial-deltaic paleosetting, and as such, the position of the sea-level curve for the Clayton Formation at this locale remains unresolved.

Walker and Coleman, 1987) has probably enhanced the formation of gullies and associated alcove-headed canyons in this portion of Georgia.

GEOLOGY

The strata composing the sidewalls of the many canyons in the Park reflect late Cretaceous to early Tertiary shallow inner-shelf to nearshore marine conditions, respectively (Eargle, 1955) [Figure 5]. Numerous geological investigations (e.g., Cooke, 1943; Eargle, 1955; Marsalis and Friddell, 1975; Reinhardt and Gibson, 1980; Sohl and Smith, 1980; Reinhardt, 1982) including several theses/dissertations (e.g., Almand, 1961; McVety, 1971; Donovan, 1986) have yielded a variety of stratigraphic and geomorphic interpretations for the area. The variation in stratigraphic interpretation results from the general lack of body fossils and the dependence on limited evidence of trace fossils, sedimentary features, and lithology. Regarding the stratigraphic complexity of the area, Eargle (1953, p. 3) stated:

> In hardly any other part of the country may a geologist find such an accumulation of weathered debris to confuse geologic detail as in the sandhills of the Coastal Plain. On the other hand, in hardly any other place may one find outcrops as well exposed as in the valley of the recently rejuvenated Chattahoochee River.

Several coordinated geological investigations during the 1980s (e.g., Reinhardt and Gibson, 1980; Donovan, 1985, 1986; Donovan and Reinhardt, 1986) resulted in the development of a widely accepted stratigraphic section for the area (Figure 5). More recent delineation of the various stratigraphic units in this portion of the state has largely built on this earlier stratigraphic framework (Friddell, 1987; Reinhardt and others, 1994). An analysis of the sedimentary deposits and structures within a sequence stratigraphic interpretation was also reported by Donovan (1993).

HYDROGEOLOGY

The hydrogeology of the section exposed in the canyons is largely controlled by two aquitards: the Paleocene Clayton Formation and a Cretaceous-age clay defined as the Perote Member (Eargle, 1955) of the Ripley Formation (Figure 6). The intervening clastic sediment in the Providence and upper portion of the Ripley are porous and permeable, coarse- to fine-grained sand with small kaolin clay lenses. While the clay stringers can create small laterally restricted perched water tables, the clastic sediments are a highly transmissive diffuse conduit for groundwater migration. Groundwater flow exhibits two gradients in the Park: south (the dominant direction) and west toward the Chattahoochee River.

The undulating upper surface of the Perote Aquitard in the Ripley Formation is intersected by several of the larger and deeper canyons. This clay aquitard has greatly reduced the rate of further vertical development and, where incised, it now controls the groundwater-supplied surface streams emanating from the floors of the many canyons.

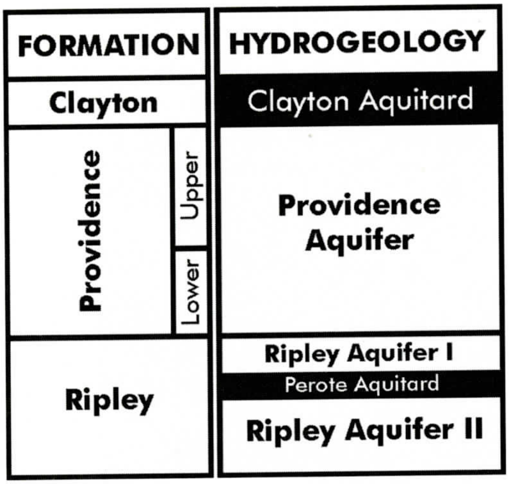


Figure 6. Hydrogeologic setting at Providence Canyon State Park. The highly porous and permeable sand comprising the Providence Formation and upper portion of the Ripley Formation is bound by two clayey aquitards. Once overland flow penetrates the Clayton Formation, the underlying clastic sediments are easily eroded and canyon formation occurs rapidly. The further incising of the canyons is limited to the groundwater table constrained by the upper surface of the Perote Aquitard. This clay unit restricts the vertical migration of groundwater flow in the subsurface and creates sapping conditions for the canyon sidewalls within the fluctuating zone of saturation.

CANYON FORMATION

The settlement of the region for agrarian purposes resulted in the clear-cutting and denudation of the land surface. Preparing the soil for planting resulted in the plowing of crop rows without regard to topography. This set the stage for uncontrolled precipitation runoff that began as rills, consolidated into gullies, and eventually incised into canyons.

The Clayton Formation thins from ridge to valley floors and, as a result, is susceptible to canyon initiation beginning in the thinly mantled stream beds. Once the gully penetrated the resistant clay layer, erosion occurred rapidly in the underlying poorly-consolidated Providence Formation. Confinement provided by the underlying Perote Aquitard enhanced the erosion of the soft and unconsolidated clastic sediments in the Providence and upper Ripley formations. Caves likely developed in the siliciclastics because groundwater piping removed the soft and easily erodible deposits (cf. Swanson and others, 1989). This would explain why the canyons were referred to as "caves" in some of the early literature (e.g., Veatch and Stephenson, 1911; Sisk, 1935; Bennett, 1939). Headward development of the ensuing canyon would continue until reaching a point where overland flow no longer incised through the Clayton Formation and the floor of the canyon was above the seasonal groundwater table. The processes involved in the overland flow development of gullies and canyons have been documented for other gully/canyon systems in the southeastern United States (see Morris, 1937; Ireland, 1939; Ireland and others, 1939).

Cliff- and spring-sapping have played significant roles at Providence Canyon as groundwater flow has continuously served to erode and transport clastic sediments out of the many canyons (cf. Morris, 1937). While groundwater sapping is widely recognized as a very important process in geomorphic development (e.g., Emmett, 1968; Higgins, 1984; Higgins and others, 1988; Howard and others, 1988; Swanson and others, 1989; Higgins and Coates, 1990), it is not presently recognized as playing an active role in the development of the canyons exposed in the Park. According to Graf and others (1987), the formation of large-scale valley networks by sapping processes is uncommon:

> ...because the processes involve a unique interplay of lithologic, stratigraphic, structural, and climate controls. Characteristic requirements include (1) a permeable aquifer underlain by an impermeable boundary, (2) a rechargeable groundwater system, (3) a free face at which subsurface water can emerge, and (4) some form of structural or lithological inhomogeneity that locally increases the hydraulic conductivity of the material and along which valleys grow. The frequency and magnitude of precipitation events are also factors.

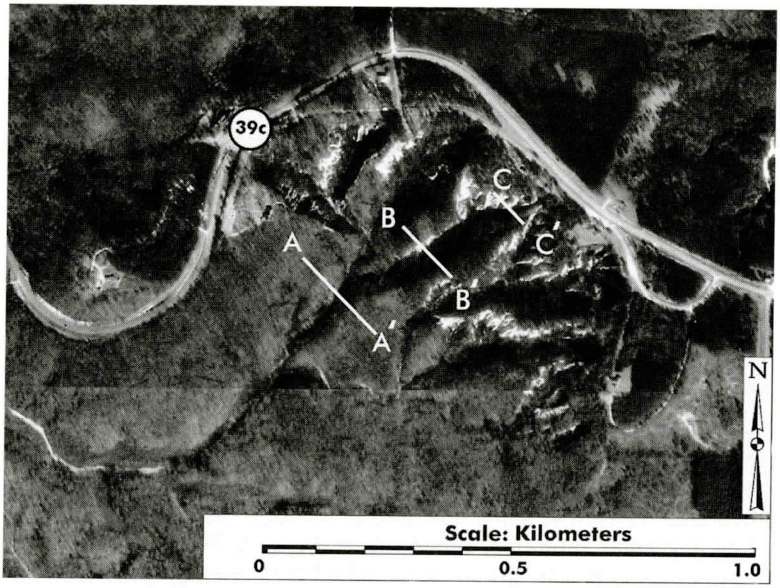


Figure 7a. U.S. Geological Survey aerial photograph of Providence Canyon State Park. Image taken February 1993. The many canyons have eroded headward nearly to the top of the topographic divide. The Perote Aquitard directs fluctuating groundwater flow within the subsurface toward the south-southwest producing groundwater sapping conditions along the base of the canyon sidewalls. Cliff- and spring-sapping serve to widen the canyon floors.

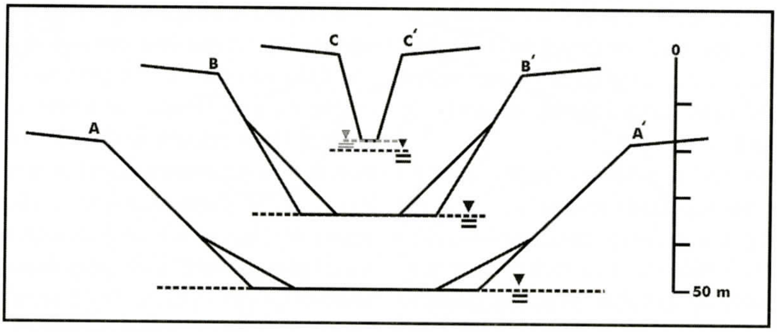


Figure 7b. Multiple cross-sections through one canyon progressing from the bottom of the canyon toward the cliff face. The canyon profile is drawn approximately to scale. Groundwater fluctuation in the subsurface is greatest at the headward end of the canyon. Once the top of the groundwater table is reached, vertical development decreases and the canyon begins to widen as a result of the erosion of the sidewalls. The lower section of the canyon floor is within the saturated zone where spring flow occurs year-round.

Although not on the same scale as the prehistoric sapping features found on the Colorado Plateau (Graf and others, 1987; Howard and others, 1988), the canyons exposed in Providence Canyon State Park exhibit all of the above-listed criteria for sapping development and provide a convenient setting in which to observe this unique process (see also Littlefield and Beck, 1983).

CANYON DEVELOPMENT

As the canyons have matured, the role of overland flow has diminished with the loss of

Figure 8. No overland surface streams flow into or through the canyons. Many of the canyon floors are completely water saturated, especially in the lower reaches, even during periods of extreme drought. A rise in the areal groundwater table contributes greater surface water volumes to the canyon floor streams and shifts their spring-fed initiation upgradient in the canyons. Sediments that choke the canyon floor streams are primarily derived from the canyon sidewalls. As a result, the canyons continue to widen in their U-shape profile.

surface streams. However, the groundwater sapping and transport of the Providence and upper Ripley clastic sediments has remained near constant due to the shallow groundwater table. Further incising of the canyons has been limited by the groundwater table and the underlying Perote Aquitard.

Water-saturated conditions on the canyon floor (above the aquitard) results in cliff- and spring-sapping and the undermining of the canyon sidewalls. While this is a rather slow process, it is easily observable over the decades that we have been investigating the park (Appendix II). The result is the transition from narrow V-shaped canyons to broadening U-shaped canyons (Figures 7a and 7b).

Today, precipitation rapidly recharges the groundwater table because of the limited cover that the Clayton Formation provides. Raising the potentiometric surface creates new seeps on the canyon floors and increases the surface area experiencing cliff- and spring sapping (Figure 8). Canyon sidewalls experience greater levels of erosion where they lie within the saturated zone. The removal of clastic sediments from the base of the canyon sidewalls results in slumping and the continual widening of the canyon floors. The rise in the groundwater table also elevates water levels in the many spring-fed canyon streams, increasing transport energy and enhancing streambed erosion. Figure 7b presents the impact that the groundwater table has on the canyon floor. The lower sections of the canyon floor remain within the zone of saturation nearly year-round, and as a result develop the wider U-shaped canyon configuration. The upper reaches of the canyon experience an elevated groundwater table only during large-scale precipitation events. As a result, the upper reaches of the canyon continues to incise its channel.

CONCLUSIONS

Likely initiated as a result of poor farming practices in the first half of the 1800s, the multiple canyons found at Providence Canyon State Park formed rapidly. Erosional equilibrium was only reached several decades later. As a result of the large-scale erosion and formation of deep canyons, the Park provides the visiting geologist with an opportunity to examine sedimentary deposits reflective of sea-level changes from low-energy, mid-shelf marine clays to high-en-

Figure 9. Groundwater table bounded U-shaped canyons. Water saturated braided stream flow occurs along the floors of these canyons. Ongoing erosion and transport of the clastic sediments along the canyon floors creates sidewall retreat. This process occurring over time will result in the eventual consolidation of the individual canyons into one large amphitheater basin.

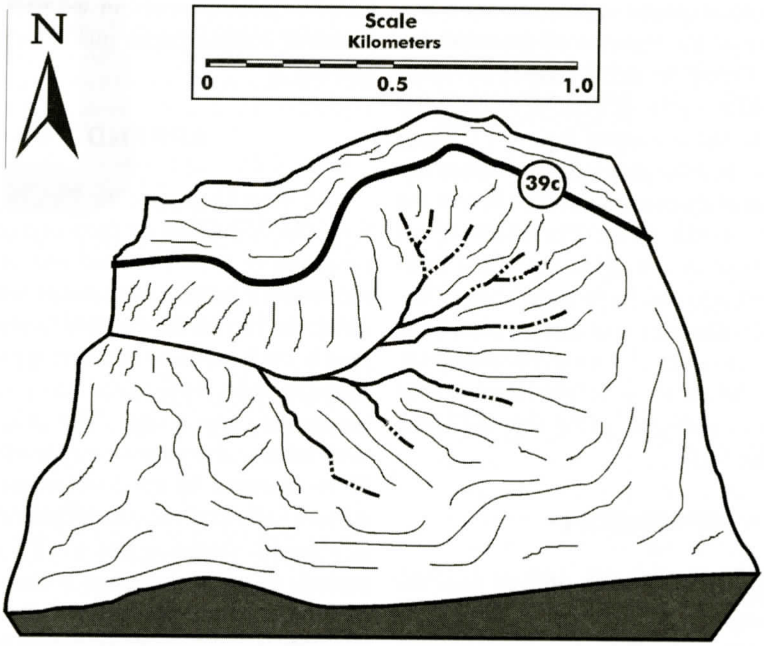


Figure 10. A diagram reflecting the predicted end of the multiple canyons composing the Park. Groundwater sapping will eventually erode the individual canyons to the topographic divide while also removing the many canyon sidewalls. The result will be the eventual consolidation of the individual canyons into one large amphitheater basin.

Table 1. Three stations were used to measure canyon sidewall erosion in a remote section of the Park. All three sites were along the top of one of the promontories between two adjacent and deep canyons.

Station	Number of Measurements	Years Covered by Measurements	Notes
L-1	11	14.5	2.13 m of sidewall removed. Station was eroded away during study.
L-2	12	16	1.83 m of sidewall removed.
L-3	11	15	31.8 cm of sidewall removed. Extensive vegetative cover limited surface erosion.

ergy, nearshore, coarse-grained marine clastic sediments. These excellent exposures occur as a result of the collapse of canyon sidewalls and the exposure of new strata.

While initiated by overland flow, the canyons today are shaped by groundwater sapping processes. Precipitation events accelerate the erosion of the canyon sidewalls as a fluctuating groundwater table shifts cliff- and spring-sapping conditions up and down the canyon floors, serving to remove clastic sediments grain-by-grain. Because of the constrained groundwater table atop the Perote Aquitard, canyon development is transitioning from narrow, steep-sided V-shaped to broad U-shaped features (Figure 9). We propose that the area will continue to develop predominately as a result of the loss of the multiple canyon sidewalls. The likely result will be the eventual consolidation of the individual canyons into one large amphitheater basin (Figure 10). The timing of this predicted end point (likely many decades away) is unknown, but it is dependent on precipitation and the varying rates of cliff-and spring-sapping along the canyon sidewalls.

APPENDIX I

Various stories have been offered over the decades describing the manner in which the various canyons in the Park may have formed. Likely one of the first to formalize one of the many legends was Sisk (1935) who attributed the erosion to runoff from a barn built in 1855. Joyce (1985) conveyed a similar story regarding water dripping from the roof of a barn. Another story suggests the canyons formed by trickles of water running down an old Indian path (Georgia Historical Commission, 1953). The only other folktale for the formation of the canyons suggests that they were started by an early settler throwing a pan of dishwater out the backdoor (Joyner, 2003). All of these stories reflect the many misperceptions of how geologic processes can create features like these canyons. Only with the recognition of the fundamental role that groundwater plays in ongoing canyon development can we understand their eventual consolidation into a large amphitheater basin.

APPENDIX II

Our investigation of the Park began in 1984, with the collection of measurements along a promontory which formed one of the canyon sidewalls (Table 1). Stations were selected along the top surface of this feature based primarily on its remote location within the Park. Measurements were made from a stationary object to the canyon edge. The canyon floors on both sides of this promontory were at minimum 25 m in depth. In most instances, the greatest surface loss occurred catastrophically as a result of sidewall slumping due to cliff-sapping. The periods of greatest erosion correlate to periods of increased precipitation. Our surface measurements fail to convey the tremendous volume of sediments removed from the sidewalls down to the canyon floors.

ACKNOWLEDGMENTS

We thank John K. Reed, A. Jerry Akridge, John Vitek, Richard Marston, Bruce O'Conner and John R. Anderson, Jr., for their helpful and constructive comments. Kathy Piselli and Thajura Harmon provided excellent reference assistance. Alan Giles, Information Geologist with the Georgia Geologic Survey, aided us by locating several survey publications important to our study of the area. For the senior author, this work does not represent the views or opinions of the U.S. Environmental Protection Agency, nor was this investigation conducted in any official capacity. Any mistakes that may remain are the responsibility of the authors.

REFERENCES CITED

Anonymous, 1981, Providence Canyon State Park, Lumpkin, Georgia: Georgia Department of Natural Resources, Atlanta, GA.

Almand, C.W., 1961, The geology of the Lumpkin Quadrangle, Stewart County, Georgia [unpublished M.S. Thesis]: Emory University, Atlanta, GA.

Beach, T., and Magilligan, F., 1993, Across the Piedmont to Providence Canyon - "The little Grand Canyon of Georgia," *in* Bederman, S.H., ed., Alligators, souseholes, and a trek down Peachtree Street: A guide to field excursions: Association of American Geographers, Washington, D.C.

Bennett, H.H., 1939, Soil conservation: McGraw-Hill - Series in Geography, New York, N.Y.

Clark, W.Z., Jr., and Zisa, A.C., 1976, Physiographic map of Georgia: Georgia Geologic Survey Map SM-4, Atlanta, GA.

Cooke, C.W., 1943, Geology of the coastal plain of Georgia: U.S. Geological Survey Bulletin 941, Washington, D.C.

Donovan, A.D., 1985, Stratigraphy and sedimentology of the Upper Cretaceous Providence Formation (western Georgia and eastern Alabama) [unpublished Ph.D. dissertation]: Colorado School of Mines, Golden, CO.

Donovan, A.D., 1986, Sedimentology of the Providence Formation, *in* Reinhardt, J., ed., Stratigraphy and sedimentology of continental, nearshore, and marine Cretaceous sediments of the eastern Gulf Coastal Plain: Field Trip 3, Society of Economic Paleontologists and Mineralogists, and American Association of Petroleum Geologists Annual Meeting, Georgia Geological Society, p. 29-44.

Donovan, A.D., 1993, The use of sequence stratigraphy to gain new insights into stratigraphic relationships in the Upper Cretaceous on the US Gulf Coast, *in* Posamentier, H.W., Summerhayes, C.P., Haq, B.U., and Allen, G.P., eds., Sequence stratigraphy and facies associations: International Association of Sedimentologists, Special Publication 18, Blackwell Scientific Publications, Boston, MA., p. 563-577.

Donovan A.D., and Reinhardt, J., 1980, Accelerated erosion (1820-1980) in the Providence Sand (Upper Cretaceous), western Georgia Coastal Plain: Geological Society of America Abstracts with Programs, v. 12(7), p. 415.

Donovan A.D., and Reinhardt, J., 1986, Providence Canyons: the Grand Canyon of southwest Georgia, *in* Neathery T.L., ed., Centennial Field Guide Volume 6: Geological Society of America, Boulder, CO., p. 359-362.

Eargle, D.H., 1953, The outcropping of Cretaceous rocks of Georgia, *in* Short contributions to the geology, geography and archaeology of Georgia, Number II: Georgia Geologic Survey Bulletin 60, Atlanta, GA., p. 1-20.

Eargle, D.H., 1955, Stratigraphy of the outcropping Cretaceous rocks of Georgia: United States Geological Survey Bulletin 1014. Washington, D.C.

Emmett, W.M., 1968, Gully erosion, *in* Fairbridge, R.W., ed., The encyclopedia of geomorphology: Encyclopedia of earth sciences series, Volume III, Reinhold Book Corporation, New York, N.Y., p. 517-519.

Friddell, M.S., 1987, Construction material potential of the Coastal Plain of southwestern Georgia: An evaluation: Georgia Geologic Survey, Bulletin 106, Atlanta, GA.

Georgia Historical Commission., 1953, Providence Canyons: Historical sign in Lumpkin, Georgia, on Georgia Highway 39C.

Georgia Historical Commission., No date, Reverend David Walker Lowe: Historical sign on park grounds, Providence Canyon State Park.

Graf, W.L., Hereford, R., Laity, J., and Young, R.A., 1987, Colorado Plateau, *in* Graf, W., ed., Geomorphic systems of North America: Centennial Special Volume 2, Geological Society of America. Boulder, CO., p. 259-302.

Higgins, C.G., 1984, Piping and sapping: Development of landforms by groundwater outflow, *in* LaFleur, R.G. ed., Groundwater as a Geomorphic Agent: Allen & Unwin, Boston, MA., p. 18-58.

Higgins, C.G., Coates, D.R., Baker, V.R., Dietrich, W.E., Dunne, T., Keller, E.A., Norris, R.M., Parker, G.G., Sr., Pavich, M., Péwé, T.L., Robb, J.M., Rodgers, J.D., and Sloan, C.E., 1988, Landform development, *in* Back, W., Rosenshein, J.S., and Seaber, E.R., eds., Hydrology: The geology of North America, Volume O-2, Geological Society of America. Boulder, CO., p. 383-400.

Higgins, C.G., and Coates, D.R., eds., 1990, Groundwater geomorphology: The role of subsurface water in Earth-surface processes and landforms: Special Paper Number 252. Geological Society of America. Boulder, CO.

Howard, A.D., Kochel, R.C., and Holt, H.E., eds., 1988, Sapping features of the Colorado Plateau: A comparative planetary geology field guide: National Aeronautics and Space Administration, SP-491, Washington, D. C.

Hyatt, J.A., and Gilbert, R., 2000, Lacustrine sedimentary record of human-induced gully erosion and land-use change at Providence Canyon, southwest Georgia, USA: Journal of Paleolimnology, v. 23, p. 421-438.

Ireland, H.A., 1939, "Lyell" gully, a record of a century of erosion: Journal of Geology, v. 47, p. 47-63.

Ireland, H.A., Sharpe, C.F.S., and Eargle, D.H., 1939, Principles of gully erosion in the Piedmont of South Carolina: United States Department of Agriculture, Technical Bulletin No. 633, Washington, D.C.

Joyce, L.G., 1985, Geologic guide to Providence Canyon State Park: Georgia Geologic Survey Geologic Guide 9, Atlanta, GA.

Joyner, J., 2003, Personal communication, Park Manager, Providence Canyon State Park, Lumpkin, GA.

Laity, J.E., and Malin, M.C., 1985, Sapping processes and the development of theater-headed valley networks on the Colorado Plateau: Geological Society of America Bulletin, v. 96, p. 203-217.

Littlefield, J., Jr., and Beck, B.F., 1983, Rates and processes of gully erosion in the Providence Canyon area, Stewart County, Georgia: Georgia Journal of Science, v. 41(1/2), p. 25.

Magilligan, F.J., and Stamp, M.L., 1997, Historical land-cover changes and hydrogeomorphic adjustment in a small Georgia watershed: Annals of the Association of American Geographers, v. 87(4), p. 614-635.

Marsalis, W.E. and M.S. Friddell., 1975, A guide to selected Upper Cretaceous and Lower Tertiary outcrops in the lower Chattahoochee River Valley of Georgia: Georgia Geologic Survey Guidebook 15, Atlanta, GA.

McVety, R.W., 1971, Steep-sided gully erosion in Stewart County, Georgia: Causes and consequences, [unpublished M.S. thesis]: Florida State University, Tallahassee, FL.

Morris, F.G., 1937, Soil erosion in south-eastern United States: Geographical Journal, v. XC, p. 361-370.

Reinhardt, J., 1982, Lithofacies and depositional cycles in Upper Cretaceous rocks, central Georgia to eastern Alabama, *in* Arden, D., Beck, B.F., and Morrow, E., eds., Proceedings of the second symposium on the geology of the southeastern coastal plain: Georgia Geological Survey Information Circular 53, Atlanta, GA., p. 89-96.

Reinhardt, J., and Gibson, T.G., 1980, Upper Cretaceous and Lower Tertiary geology of the Chattahoochee River Valley, western Georgia and eastern Alabama, *in* Frey, R.W. ed., Excursions in Southeastern Geology Volume II: Field trip guidebook for the Geological Society of America Annual Meeting, American Geological Institute, Falls Church, VA., p. 385-392.

Reinhardt, J., Prowell, D.C., and Christopher, R.A., 1984, Evidence for Cenozoic tectonism in the southwest Georgia Piedmont: Geological Society of America Bulletin, v. 95, p. 1176-1187.

Reinhardt, J., Schindler, J.S., and Gibson, T.G., 1994, Geologic map of the Americus 30' X 60' quadrangle, Georgia and Alabama: United States Geological Survey, Miscellaneous Investigations Series Map I-2174, Washington, D.C.

Sisk, L.J., 1935, All this started from the trickle from a roof: Soil Conservation, v. 1(2), p. 12-13.

Sohl, N.F., and Smith, C.C., 1980, Notes on Cretaceous biostratigraphy, *in* Frey, R.W. ed., Excursions in Southeastern Geology Volume II: Field trip guidebook for the Geological Society of America Annual Meeting, American Geological Institute, Falls Church, VA., p. 392-402.

Stephenson, L.W., 1928, Structural features of the Atlantic and Gulf Coastal Plain: Geological Society of America Bulletin, v. 39, p. 887-900.

Swanson, M.L., Kondolf, G.M., and Boison, P.J., 1989, An example of rapid gully initiation and extension by subsurface erosion: Coastal San Mateo County, California: Geomorphology, v. 2, p. 393-403.

Trimble, S.W., 1974, Man-induced soil erosion on the southern Piedmont, 1700-1970: Soil Conservation Society of America, Ankeny, IA.

Twidale, C.R., 1968, Anthropogenic influences in geomorphology, *in* Fairbridge, R.W., ed., The encyclopedia of geomorphology: Encyclopedia of earth sciences series, Volume III., Reinhold Company, New York, NY., p. 15-18.

Veatch, O., 1909, Second report on the clay deposits of Georgia: Geological Survey of Georgia, Bulletin No. 18, Atlanta, GA.

Veatch, O., and Stephenson, L.W., 1911, Preliminary report on the geology of the coastal plain of Georgia: Geological Survey of Georgia, Bulletin 26, Atlanta, GA.

Walker, H.J. and Coleman, J.M., 1987, Atlantic and Gulf Coastal Province, in Graf, W.L., ed., Geomorphic systems of North America: Geological Society of America, Centennial Special Volume 2, Boulder, CO. p. 51-110.

Wells, N.A., and Andriamihaja, B., 1993, The initiation and growth of gullies in Madagascar: Are humans to blame?: Geomorphology, v. 8, p. 1-46.

SOUTHEASTERN GEOLOGY
V. 43, No. 1, August 2004, p. 51-55

A PTEROSAUR FEMUR FROM THE UPPER CRETACEOUS OF NORTH CAROLINA

DAVID C. PARRIS AND BARBARA SMITH GRANDSTAFF

Bureau of Natural History, New Jersey State Museum
P. O. Box 530, Trenton, NJ 08625-0530

DONALD CLEMENTS

67 South Hummingbird Lane
Rocky Point, NC 28457

ABSTRACT

Relatively few pterosaurs have been reported from the Maastrichtian Stage and these are naturally of particular interest, approaching the Cretaceous-Tertiary boundary and extinction. Few have been reported of any age from eastern North America and none from North Carolina although its extensive area of Cretaceous outcrops is the greatest of any eastern state. The well preserved specimen reported here comes from the Rocky Point Member of the Peedee Formation at a well known locality, the East Coast Limestone Quarry in Maple Hill, Pender County, North Carolina. The Peedee Formation is generally correlated to the Maastrichtian Stage, and this is confirmed by other fauna from the locality, including *Belemnitella americana* (Morton), *Sphenodiscus lobatus* (Tuomey), *Exogyra costata* (Say), *Cimoliasaurus magnus* (Leidy), and *Peretresius ornatus* (Leidy). This fauna compares well with that of the Navesink Formation of New Jersey.

The specimen is a right femur of preserved length 76.7 mm; its original length is estimated at 85 mm. The observed bone thicknesses are less than one mm, but despite its delicacy the specimen is uncrushed. In size, proportions, and all surfaces it resembles a femur referred to *Azhdarcho lancicollis* (Nesov). It may belong to the Azhdarchidae, the family to which many Maastrichtian pterosaurs belong.

INTRODUCTION

The few pterosaur records of eastern North America were summarized by Russell (1988) and Wellnhofer (1991), who also summarized the few records of pterosaurs of Maastrichtian age. Detailed descriptions were given by Baird and Galton (1981), Schwimmer and others (1985), and Wellnhofer (1978). None have previously been reported from North Carolina, despite its extensive area of Cretaceous rocks. The specimen reported here is also of interest for being one of the last of the pterosaurs, coming from a stratigraphic level which is close to the Cretaceous-Tertiary boundary.

The eastern part of North America, presumably an isolated subcontinent during the Late Cretaceous Period (Smith and others, 1994), has produced much new faunal information during recent decades. Nonmarine taxa are sufficiently well known to demonstrate that there was substantial endemism. Possibly this subcontinent was the place of origin of various major taxonomic groups (Denton and O'Neill, 1995). However, the pterosaurs were less bounded by geographic barriers and could contrast with the non-volant vertebrate fauna, possibly having a more cosmopolitan aspect.

Institutional abbreviations used herein are: FMNH- Field Museum of Natural History; NJSM- New Jersey State Museum.

LOCALITY AND STRATIGRAPHY

The specimen (NJSM 18772) was collected by one of the authors (D.C.) at the East Coast Limestone Quarry near Maple Hill, Pender County, North Carolina in 1995 (Figure 1). The

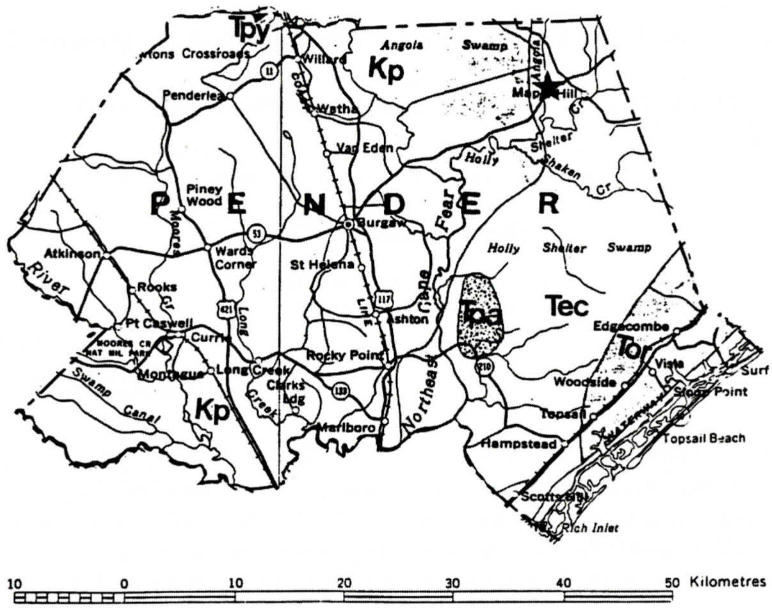


Figure 1. Geology of Pender County, North Carolina, position of the East Coast Limestone Quarry shown by star. Geologic mapped units are Kp: Peedee Formation; Tpa: Beaufort Formation; Tec: Castle Hayne Formation; Tor: River Bend Formation; Tpy; Yorktown and Duplin Formations. After North Carolina Geological Survey (1985).

quarry had suspended operations by 1997. It is located on State Route 53 just west of the intersection of State Routes 50 and 53, and indicated on the Maple Hill 7 ½' Quadrangle (United States Geological Survey). It is one of several operations previously described by Feldmann and others (1998), and only a few details will be repeated here.

Exposed at the greatest depths of the quarry were several meters of Peedee Formation (Rocky Point Member), which included the fossiliferous horizon. The overlying Eocene Castle Hayne Formation was the horizon of the product rock, primarily the New Hanover Member, but also partially the Comfort Member. See Feldman and others (1998) for detailed location and comparable stratigraphic section, and Carter and others (1988) for further descriptions. Associated faunal specimens were collected from the horizon as listed in Table 1. The precise horizon cannot be determined because the specimens come from spoil piles in the quarry, but the matrix adhering to the specimens leaves no doubt as to their origin.

Originally described informally by Swift and Heron (1969), the name Rocky Point Member was formalized by Wheeler and Curran (1974). It was subsequently renamed the Scotts Hill Member by Ward and Blackwelder (1978). The original name was defended by Harris and others (1986). Recent literature is either ambiguous about the name (Sohl and Owens, 1991) or uses the term Rocky Point Member (Zarra, 1991), as we do.

The Rocky Point Member at its type locality is approximately 10.5 meters of pelecypod biosparrudite, unconsolidated quartz arenite, and alternation of the two lithologies, (Wheeler and Curran, 1974). Our locality, about 25 kilometers northnortheast of the type locality, shows a much thinner section. Only about 1 meter of indurated rock is present above a meter of arenite that has a higher clay content than at the type locality. A later biozone of the Peedee, the *Haustator bilira* Zone (Sohl and Owens, 1991), is not present at the East Coast Limestone Quarry, indicating that the rocks are earlier than latest Maastrichtian. The presence of *Belemnitella*

Table 1. Fauna of the Rocky Point Member at East Coast Limestone Quarry, Maple Hill, Pender County, North Carolina

Bryozoa, undetermined
Gastropoda, undetermined
Sphenodiscus lobatus (Tuomey)
Belemnitella americana (Morton)
Cucullaea sp.
Crassatellites sp.
Pycnodonte sp. ("Gryphaea")
Spondylus sp.
cf. *Cardium* sp.
Pelecypoda, undetermined
Exogyra costata (Say)
Avitelmessus grapsoides Rathbun
Opthalmoplax stephensoni Rathbun
**Catopygis mississippiensis* Cooke
**Hardouinia aequoria* (Morton)
Hardouinia mortoni (Michelin)
**Faujasia chelonium* Cooke
Linthia variabilis Slocum
**Cardiaster leonensis* Stephenson
**Lefortia trojana* Cooke
Porosoma sp,
Enchodus sp.
Peretresius ornatus Leidy
Chelonia, undetermined
Mosasauridae, undetermined
Crocodilia, undetermined
Cimoliasaurus magnus Leidy
Species prefixed with an asterisk were reported from the Middle and Late Maastrichtian of the Gulf Coast States by Cooke (1953) indicating a Gulf Coast influence on the fauna of the Peedee Formation during the Maastrichtian.

Table 2. Measurements of NJSM 18772 (in mm). cf. Azhdarchidae (Refer to Figure 2)

Total Length (actual)	75.7
Total Length (restored, estimated)	85
Maximum Thickness (Position A)	11.5
Circumference (Position A)	40.0
Maximum Thickness (Position B)	10.0
Circumference (Position B)	34.0
Maximum Thickness (Position C)	13.0
Circumference (Position C)	44.0

americana as an indicator of early Peedee deposition makes the approximate age of the rocks lower or middle Maastrichtian (Sohl and Owens, 1991). It should be noted, however, that *B. americana* is present at the type locality of the Rocky Point Member, and that section is considered Late Maastrichtian by Sohl and Owens (1991). Detailed microscopic studies of the foraminifera and palynomorphs would provide a more accurate age determination for this locality. The matrix of the pterosaur specimen is a calcareous glauconitic arenite.

DESCRIPTION

The specimen (NJSM 18772) is a right femur of preserved length 76.7 mm (Figure 2). It is virtually undistorted, but significant portions of both ends are missing and the condylar and trochanteric shapes are to some degree speculative. However, the original length is readily estimated at approximately 85 mm. Additional measurements (Table 2) are sufficient to establish the proportions very well.

Where broken, the thickness of the surficial bone can readily be determined as less than one mm. The femoral adductor ridge along the diaphysis is well developed and is the most conspicuous surface feature. Following criteria established by Bennett (1993), there are no indications of juvenile morphology.

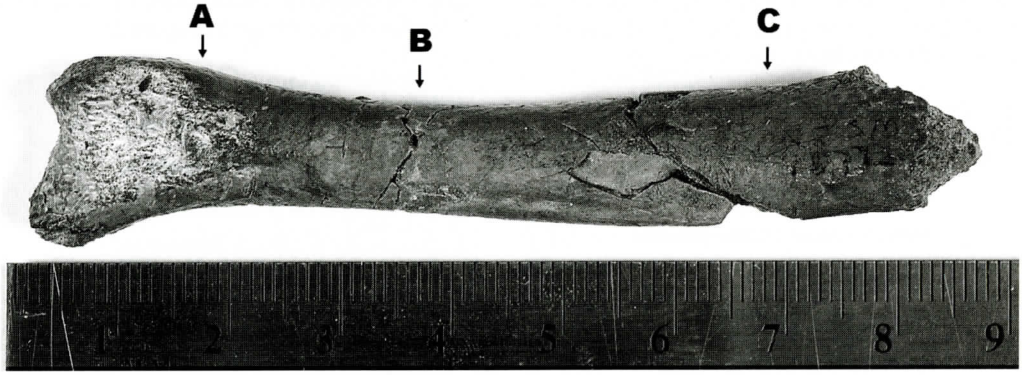


Figure 2. Pterosaur femur, NJSM 18772, cf. Azhdarchidae. Posterior view with positions of measurements A-C indicated along shaft. Scale bar one cm.

DISCUSSION

The general size (length) of the bone and its Maastrichtian age suggested comparison to the genus *Nyctosaurus*, which is typical of the Niobrara Formation (Coniacian-Santonian), but is thought to have ranged much later as well. A comparison with femora of FMNH-P-25026 showed significant differences, however. The North Carolina specimen is only slightly longer than the femora of FMNH-P-25026, but the apparent widths of crushed femora of the latter specimen are not as broad as the uncrushed shaft of the North Carolina specimen. If all were uncrushed, the shaft diameter of the North Carolina specimen would likely be three times that of the Niobrara genus.

The proportions of NJSM 18772 actually approach those of femora attributed to pterosaurs of the Family Azhdarchidae (Padian, 1986), which includes most determinable Maastrichtian pterosaurs. Although some members of the family were very large reptiles (indeed the largest of all flying creatures) it is known that smaller members existed as well. We refer the specimen tentatively to that family with the implication of the existence of an as yet poorly known genus of pterosaur at that time.

The femur referred to *Azhdarcho lancicollis* by Nesov (1984) is very similar in all measurements and proportions to the specimen described here, judging from the published illustration. If Nesov's specimen is correctly referred to *Azhdarcho*, this present specimen may also be referable to that genus.

ACKNOWLEDGMENTS

Discussions with Drs. Kevin Padian, S. Christopher Bennett, Wann Langston and David Unwin were all essential to the production of this report. Amateur paleontologists L.G. "Mike" Milton, Jr., Keith Sturgeon, and Mick Chou assisted in the field inspection of the locality, adding their expertise in compilation of the faunal list. Access to the site was generously permitted by Bobby and Connie Goodson, owner/operators of the quarry. We also thank William Simpson of the Field Museum of Natural History for access to comparative material. Drs. William B. Gallagher and Robert Ramsdell and Ms. Shirley Albright reviewed the manuscript. Elsayed Aboyoussef assisted with the illustrations. Funds in support of the field work and publication were provided by the Friends of the New Jersey State Museum from the Horace G. Richards Fund. This discovery was originally announced at Dinofest in Philadelphia (Parris and others, 1998). Reviews by Drs. Kevin Padian and Charles Ciampaglio resulted in substantial improvements.

REFERENCES

Baird, D. and Galton, P.M., 1981, Pterosaur bones from the Upper Cretaceous of Delaware. Journal of Vertebrate Paleontology v.1,p.92-106.

Bennett, S.C., 1993, The ontogeny of *Pteranodon* and other pterosaurs. Paleobiology v.19,p.92-106.

Carter, J.G., Gallagher, P.E., Valone, R.E., and Rossbach, T.J., 1988, Fossil Collecting in North Carolina. North Carolina Department of Natural Resources and Community Development; Geological Survey Section, Bulletin 89, 89 pp.

Cooke, C.W. 1953. American Upper Cretaceous Echinoidea. U. S. Geological Survey Professional Paper 254A,44 pp.

Denton, R.K., Jr. and O'Neill, R.C., 1995, *Prototeius stageri*, gen. et sp. nov., a new teiid lizard from the Upper Cretaceous Marshalltown Formation of New Jersey with a preliminary phylogenetic revision of the Teiidae. Journal of Vertebrate Paleontology 15:235-253.

Feldmann, R.M., K.L. Bice, C.S. Hopkins, E.W. Salva, and K. Pickford, 1998, Decapod Crustaceans from the Eocene Castle Hayne Limestone, North Carolina, Paleoceanographic Implications. Journal of Paleontology v.72, 1-supplement, Memoir 48, 28 pp.

Harris, W.B., Thayer, F.A., and Curran, H.A., 1986, The Cretaceous Tertiary Boundary on the Cape Fear Arch, North Carolina, U.S.A. Cretaceous Research 7:1-17.

Nesov, L.A., 1984, Upper Cretaceous Pterosaurs and Birds from central Asia, Paleontological Journal 1984: p.38-49.

North Carolina Geological Survey, 1985. Geologic Map of North Carolina. Map: Scale 1:500,000.

Padian, K. 1986. A taxonomic note on two pterydactyloid families. Journal of Vertebrate Paleontology v.6, p.289.

Parris, D. C., Grandstaff, B. S., and Clements, D., 1998, A pterosaur femur from the Upper Cretaceous of North Carolina (Abstract). Dinofest Symposium (Academy of Natural Sciences of Philadelphia).

Russell, D.A., 1988, A checklist of North American marine Cretaceous vertebrates including fresh water fishes. Occasional Papers of the Tyrrell Museum of Paleontology v.4, p.1-58.

Schwimmer, D.K., Padian, K., and Woodhead, A.B., 1985, First pterosaur records from Georgia: Open marine facies, Eutaw Formation (Santonian). Journal of Paleontology v.59 p.674-676.

Smith, A.G., Smith, D.G., and Funnell, B.M.,1994, Atlas of Mesozoic and Cenozoic Coastlines. Cambridge University Press.

Sohl. N.F. and Owens, J.P., 1991, Cretaceous stratigraphy of the Carolina Coastal Plain, *in* Morton, J.W. and Zullo, V.A., eds. 1991, The Geology of the Carolinas. Carolina Geological Society Fiftieth Anniversary Volume: 191-220.

Swift, D.J.P., and Heron, S.D., Jr. 1969, Stratigraphy of the Carolina Cretaceous: Southeastern Geology v.10, p. 201-245.

Ward, L.W. and Blackwelder, B. W., 1978, Scotts Hill Member (New Name) of the Cretaceous Peedee Formation of Southeastern North Carolina and East-Central South Carolina. U. S. Geological Survey Bulletin 1482-A:A87-A88.

Wellnhofer, P., 1978, Handbuch der Palaoherpetologie/ Encyclopedia of Paleoherpetology, Teil 19 Pterosauria. Stuttgart, Gustav Fischer Verlag. 82pp.

Wellnhofer, P., 1991, The illustrated encyclopedia of pterosaurs: London, Salamander Books Ltd. 192pp.

Wheeler, W.H. and Curran, H.A., 1974, Relation of Rocky Point Member (Peedee Formation) to Cretaceous-Tertiary boundary in North Carolina. American Association of Petroleum Geologists Bulletin 59:1751-1757.

Zarra. L., 1991, Subsurface Stratigraphic Framework for Cenozoic strata in Brunswick and New Hanover Counties, North Carolina. North Carolina Geological Survey Information Circular 27. Map Sheet.